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An Artificial Neural-Network Simulation of Auditory Intensity Perception and Profile Analysis

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ABSTRACT

This paper describes a computer simulation of human auditory intensity discrimination. There are currently two different views of how intensity discrimination is carried out by human listeners. The traditional view holds that a listener successively compares the acoustic energy between two sounds and selects the louder of the two. A more recent view, called profile analysis, suggests that a listener simultaneously compares the spectral profile within each sound individually. In other words, the timbre or the perceived spectral shape of the sound is also considered. The computer simulations replicated a study by Green, Kidd, & Picardi (1983) in which the interval between the sounds was varied. Results from the simulations are consistent with results obtained from human data.

Introduction

In the past five years there has been a growing interest in a class of adaptive computer models known as artificial neural networks. The discipline dedicated to the study of neural networks is a multidisciplinary field which involves researchers from diverse backgrounds including computer science, neuroscience, cognitive science and psychology. The application of neural networks is uniquely defined within each discipline. For example, computer scientists are interested in applying neural networks as a technology to solve difficult engineering problems encountered in robotics, computer-assisted pattern recognition and artificial intelligence. Neuroscientists are principally interested in building computational models of neurophysiological systems, and artificial neural networks provide them with a useful tool for modeling.

Cognitive science and psychology have embraced this technology as a theoretical framework to help explain, understand, and predict human performance. Symbolic models such as expert systems have enjoyed much success when ap-

plied to rule-based decision making problems. However, these same symbolic models have failed abysmally when confronted with perceptual pattern recognition and classification problems—the very problems at which artificial neural networks excel. The neural network paradigm offers a powerful alternative to the traditional symbolic models so widely applied in the artificial intelligence and cognitive psychology disciplines.

A defining characteristic of artificial neural networks is their parallel architecture. Unlike conventional digital computers, which have a single central processing unit executing instructions sequentially, artificial neural network models have many simple processors acting together concurrently. Each processing element is capable of computing only a few very simple logical or algebraic operations. The real strength of neural network models comes from the interaction of large assemblies of processing elements acting together in parallel.

Processing elements are arranged in layers. The connections between processing elements are assigned numerical values which are referred to as weights. The architecture of a neural network is tailored to each individual application or problem. The simplest neural network architecture consists of two layers of processing units. More complex architectures support three or more layers. Due to the fact that computers with true parallel architectures—sometimes referred to as neurocomputers—are not yet widely available, neural network simulations of parallel architectures are carried out on digital computers with conventional von Neumann architectures.

Another important distinction between the processing in neural networks as compared with conventional computing is the way that information is represented. In neural networks, knowledge is not stored locally or associated with an address in memory. Rather, concepts are represented implicitly by a pattern of activation over a large number of processing units. Information, or knowledge is encoded in the connections themselves, and not in the processing elements which serve only as computing devices. This results in a system which is very fault tolerant, and degrades gracefully if a subset of processing units fails or if the input data become corrupted or degraded by noise.

Perhaps the most remarkable aspect of neural networks is their ability to learn by example, without being programmed by a human. Through the application of an iterative training algorithm, a neural network can learn to associate one set of patterns with another set of patterns. In essence, a function is computed by the network which maps a set of input patterns onto an output pattern. The connection weights of a neural network implement this mapping. The proper set of weights to compute this function is usually never known a priori. So various statistical training algorithms have been developed to adjust the weights.

Perceptual psychologists have become interested in experimenting with

neural networks for several reasons. First, due to the fact that the parallel architectures of neural networks lend themselves to perceptual pattern recognition problems, they provide psychologists with a superior computational model of the underlying perceptual processes. Second, parallel models not only provide a better theory of the processes, their architecture is based on gross biological principles understood about the brain. And third, neural networks can learn by being trained, can adapt to changing input parameters, and can generalize to novel patterns never seen before. This is one of the cornerstones of human intelligence and performance, and has been neglected in the past with the statistical models so pervasive in the psychophysical literature. In sum, neural networks are able to demonstrate the type of flexible and adaptive performance which conventional symbolic models lack, while also accounting for perceptual learning (Clark, 1989).

In the present research program an artificial neural network was applied to a classic problem studied by perceptual psychologists for over one hundred years; How can we explain the ability of a listener to discriminate a difference in intensity between two simple sounds? In a typical intensity-discrimination experiment, two sounds are presented successively, separated by a brief interstimulus interval. Both sounds contain a pure tone (known as the standard) and one contains the standard with a small increment (known as the signal). The observer is forced to decide which sound pattern contains the standard plus signal. The traditional explanation given to account for this phenomenon states that a listener performs the task by choosing the tone with the greater acoustic energy.

In contrast to the traditional view is a more current view of intensity discrimination and signal detection which David Green and his colleagues have referred to as auditory profile analysis (Green, 1988). The stimuli used in profile analysis experiments are complex broadband sounds, in contrast to the pure-tones typically used in psychoacoustic experiments. In a profile analysis task, the sound with the signal component may have less overall energy than the standard; hence, intensity discrimination will not work. The judgment of whether a signal is present or absent must be made by considering the internal shape of the spectrum as opposed to comparing the differences in energy between sounds.

Despite the fact that this phenomenon has been studied so extensively, there is still not a comprehensive theory of intensity perception and spectral shape discrimination which can account for the entire body of empirical data. This provided the motivation for performing the computer simulations in the present study.

In this study an artificial neural network was trained in both an intensity discrimination and profile analysis task. The independent variable of interest

was the duration of the interstimulus interval (ISI) between the presentation of each sound pattern in a two-alternative forced choice task. The computer simulations carried out here replicated a study originally done by Green, Kidd, & Picardi (1983). Four separate computer simulations were performed, each of which corresponded to one of the four experimental conditions in the original Green et al. study.

Artificial Neural Networks

The early roots of artificial neural network models were as simple pattern associators. The first neural networks widely discussed in the scientific literature were known as "Perceptrons," a name coined by Frank Rosenblatt in the late 1950's. Perceptron models were often applied to pattern-recognition and classification problems. Through training with an iterative learning algorithm, perceptrons could learn to associate a set of input patterns with an output pattern which coded category membership.

Initially, perceptrons held much promise for modeling perceptual pattern recognition processes. Rosenblatt proved an important mathematical theorem, known as the perceptron convergence theorem (Rosenblatt, 1962). This theorem guaranteed that if a set of input patterns are learnable by a perceptron, then this learning procedure would converge on a set of connection weights which enable a perceptron to adequately represent the problem. This proof was an important contribution to both the machine learning field in engineering and learning theory in psychology.

However, as researchers began to experiment with perceptrons it soon became apparent that there was a class of problems that a simple linear perceptron could not solve. A severe limitation placed on the perceptron by the learning algorithm enabled it to adjust only one layer of adaptive weights. As a result, the perceptron could only solve problems which were linearly separable, meaning that a perceptron could only perform a linear mapping between the set of input patterns and output or "target" pattern. This limitation was formally stated in a book called "Perceptrons" written by Marvin Minsky and Seymour Papert (1969). The classic example given in "Perceptrons" was the exclusive-or (XOR) logic operation, which a perceptron could not compute. As a result of Minsky and Papert's critical evaluation of the perceptron model, coupled with its inherent limitations in the types of problems which could be represented, research with neural networks died out in the late 1960's.

In the past five years there has been a resurgence of interest in adaptive neural network models. This is due to the fact that a powerful new learning algorithm has been discovered which allows neural networks composed of multiple layers of adaptive weights to be trained (Rumelhart, Hinton, & McClelland, 1986).

Multi-layer networks with three or more layers incorporate a middle layer of 'hidden' units between the input and output layers. By adding an additional hidden layer, the neural network can recode the input patterns into a higher-order internal representation. The multi-layer networks have been able to solve many of the problems that a simple linear perceptron was unable to solve previously, such as the XOR problem.

Network architecture. The architecture of the neural networks used in the present simulations is illustrated in Figure 1. A two-layer fully-interconnected feed-forward artificial neural network was used. There are two layers of processing elements, an input and an output. All input units are fully-connected to the output unit. There is no feedback from the output unit back to the inputs; activation can only flow forward.

Only two layers of processing elements were used in the simulations discussed in this study, as a multi-layer network with hidden units was not needed to perform the task. More complex architectures often support recurrent connections where activation is passed-backwards from the output layer to the input layer, or laterally to other units within a layer. Connections between non-adjacent layers are also possible. The connection weights themselves are stored in a weight matrix. There is an additional weight associated with each output unit called a bias. The bias value may be thought of as threshold term that influences the amount of input needed to elicit a response by that particular unit. The bias values are stored in the weight matrix as well.

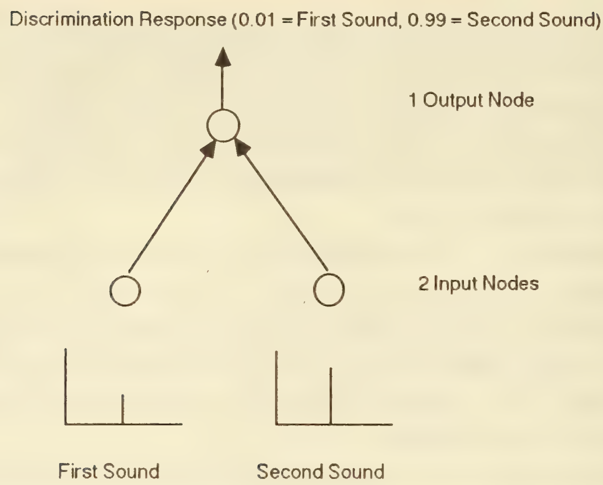
Network output function. The transfer function for each neuron is known as an activation function. The activation function defines an input to output relationship for a processing element by establishing an output value for a given input value. The output for any unit O_j is a non-linear function of the weighted sum of its inputs plus a threshold or bias value

$$O_j = S(\sum_{i}^{n} O_i W_{ji} + B_j)$$

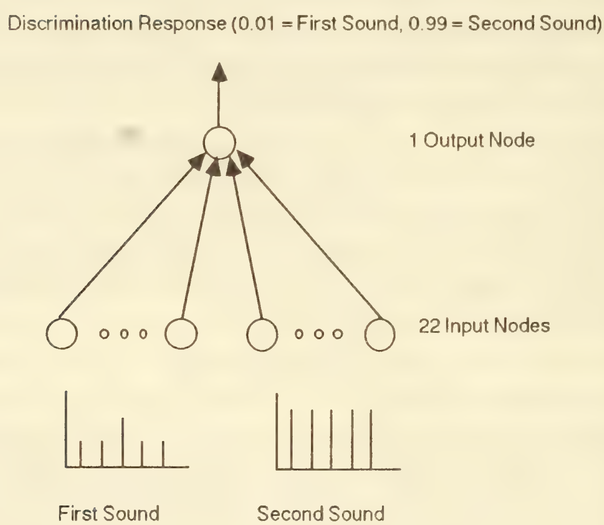
where W_{ji} is the strength of the connection between units i and j and B_j is the bias value or threshold for unit j. S(x) is a nonlinear squashing function which remaps the sum of inputs into the range 0.0 to 1.0. In the present research a sigmoidal squashing function was used

$$S(x) = 1/(1 + \exp(-x)).$$

This function "squashes" positive values into the range 0.5–1.0 and negative values into the range 0.0–0.5. As a result of the squashing function, the output elicited from a processing unit will not be at its maximum unless it receives a net positive input greater than its bias value.



a. Schematic of a 2-1 feed-forward architecture used to detect the presence of a signal increment to a sinusoid.



b. Schematic of a 22-1 feed-forward architecture used to detect the presence of a signal in a complex sound.

Fig. 1. Schematic of 2-1 & 22-1 neural-network architectures trained with the back-propagation learning algorithm.

The learning algorithm. The learning algorithm used to adjust the connection weights of the network during training is the popular back-propagation algorithm. Back-propagation is a training technique which allows multi-layer networks to establish an optimal mapping between input and output units (Rumelhart, Hinton, and McClelland, 1986).

Training involves two steps. At the outset all of the connection weights are initialized to small random values. In the first step, input patterns are applied to the network. The input vector is fed forward through the network and an output value is computed. This output value (or observed value) is then compared with a target value, which is the desired output value. If there is a discrepancy between the observed value and the target value then an error signal is generated.

The second step in back-propagation involves a backward pass through the network. The error signal is propagated backwards through the network, and each of the weights between the output unit and the input units are adjusted by an amount proportional to the error term. A similar adjustment is made to the bias term.

During the testing phase, the connection weights are fixed and cannot be modified. Testing patterns are applied as input and the output or response of the network is measured. In the case of the simulations discussed in this study, the network was only required to perform two-category classification. The task required of the network was to select the interval which contained the signal increment.

Stimulus Conditions

Two methods were used to select the level of the background or masker components of the stimulus patterns. In each case, the levels of the maskers were sampled randomly from a uniform distribution. However, the critical distinction is whether the level of the maskers remains fixed across trials, or is varied randomly within trials.

The first method used a *between-trial* variation. In this case the amplitudes of the masker components in the first and second sound-intervals are equivalent. The second method used a *within-trial* variation. The levels of the maskers in a stimulus pair are chosen independently of one another, and the levels of the maskers for the first and second patterns usually differ.

Three different sets of stimulus patterns were generated for the between-trial variation method. They are referred to as the single-sinusoid condition, the uniform-spectrum condition, and the multi-component condition. In the single-sinusoid condition (Figure 2a), there is only one frequency component, the signal increment was always added to this. In the uniform-spectrum condition, (Figure 2b) there are multiple frequency components. The signal in this instance

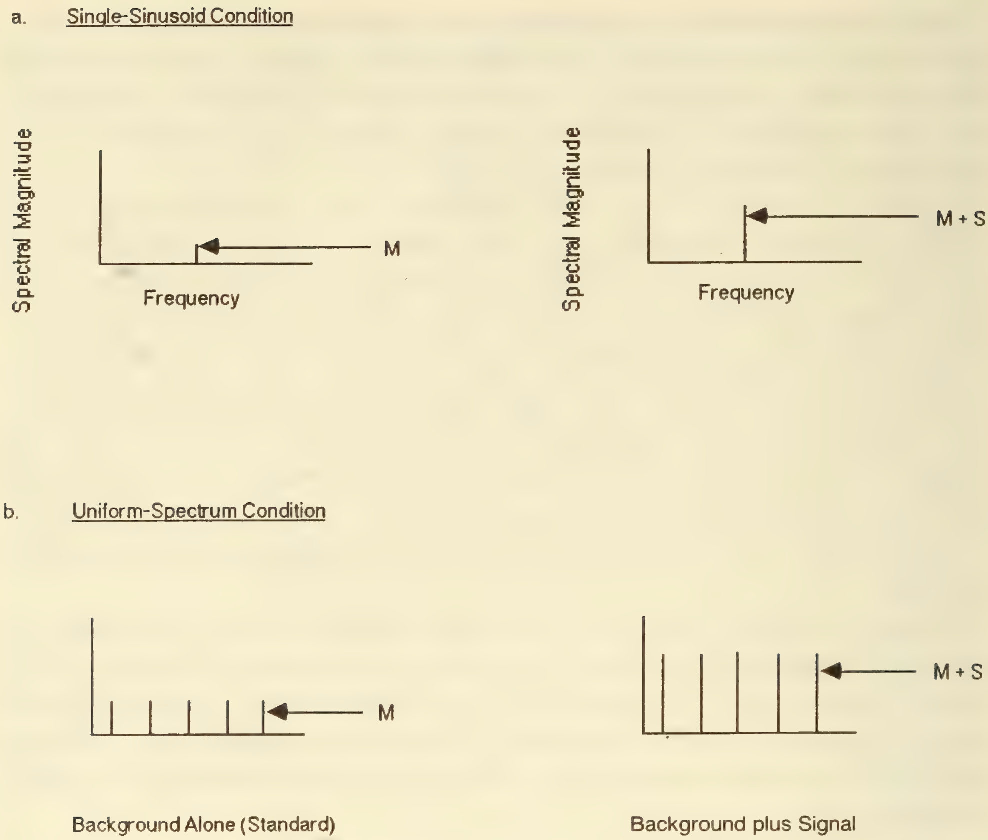


Fig. 2. Schematic line spectra of test sounds for the single-sinusoid and uniform-spectrum conditions. S = Signal and M = Masker.

is always added to each of the background components in the tonal complex. In both of the above conditions the overall shape of the stimulus remains the same across intervals of a trial.

In the multi-component condition the signal increment is always added to the center component of a multitonal complex (Figure 3a). The amplitudes of the maskers in both sounds are identical. However, a critical difference between this condition and the conditions in Figure 2 is that information regarding the spectral shape of the stimulus is also available to the listener. The signal can now be depicted as a bump occurring in the center of a symmetric tonal complex.

A fourth set of sounds was generated using the *within-trial* variation procedure. This will be referred to as the profile-analysis condition (Figure 3b). As in the multi-component condition, the profile stimuli are composed of multiple frequency components which provide information on the spectral shape of the stimulus. However, unlike the above conditions, the levels of the maskers are

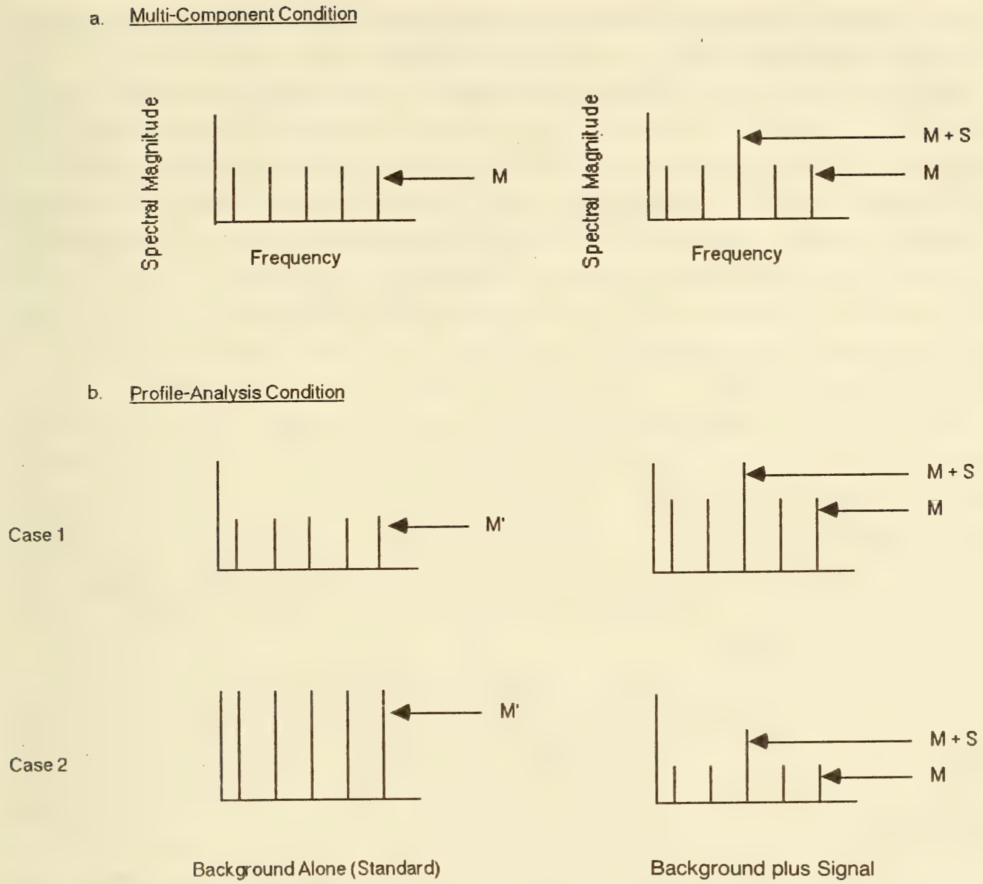


Fig. 3. Schematic line spectra of test sounds for the multi-component and profile conditions. In the profile analysis condition the masking level will be of less (Case 1) or greater (Case 2) value than the amplitude of the background plus signal. S = Signal and M & M′ = Masker Components.

selected randomly within trials (as well as between trials). Case 1 describes the task where the amplitude of the standard is less than the background-plus-signal whereas in Case 2 the amplitude of the standard is greater than the background-plus-signal. To select the interval with the signal component, amplitude cues are no longer sufficient and the shape or profile of the stimulus must be analyzed.

Traditional View

The traditional view of intensity perception has evolved from both empirical studies as well as classical psychoacoustic theory. This view of auditory processing assumes three serial stages (Green, 1988). In the first stage, auditory signals are passed through a bank of linear, critical-band filters, each of which is tuned to pass a limited band of acoustic energy. Each auditory filter is assumed to have

a critical bandwidth. Energy which falls within the boundaries of a critical band is passed and energy falling outside of a critical band is rejected.

In the next stage of processing a single channel is selected, and an energy detector measures the acoustic energy present within the band at the signal frequency in each sound interval. A sensory representation of each stimulus is encoded and stored in a rapidly decaying short term memory. Durlach & Braida (1969) have referred to this form of representation as "sensory encoding." Sensory decay results from the tendency of the memory trace to become corrupted with internal neural noise and deteriorate with time. In the final stage of processing, a successive comparison is performed between the two sensory traces in order to report whether they are same or different, or one is louder or softer.

A shortcoming of the traditional explanation of intensity discrimination is that it may tell us more about the psychoacoustic task itself, rather than about the underlying psychological processes. In an intensity discrimination task, a listener need only select the sound with the greater overall energy. This perspective is consistent with the literature on critical band theory. Only energy which falls inside of a critical band filter is attended to, and energy falling outside of the critical band is ignored.

While research into pure-tone intensity discrimination has been useful in developing an understanding of basic auditory processes, the stimuli used in those experiments are highly synthetic and arbitrary in their structure. Most importantly, these types of sounds are rarely encountered in the real world, and this has placed a severe constraint on the development of psychoacoustic theory. The work on auditory profile analysis has begun to address this weakness, and has put in place a foundation for development of auditory models which have explanatory power that can capture the way that the auditory system deals with complex signals encountered in the real world.

Profile Analysis View

The profile analysis view assumes the same psychophysical signal processing stages as the traditional view. However, in a profile analysis task both the listening strategies and memory processes differ from those used in pure-tone intensity discrimination. Profile analysis emphasizes a simultaneous or broadband comparison process within a sound across frequency channels rather than a successive comparison between critical bands. Green has referred to this broadband spectral analysis as a global comparison process (Green, 1983).

Some of the most dramatic evidence of broadband listening comes from experiments which varied the bandwidth of the stimulus out to regions beyond one critical band. It has been demonstrated that there is a consistent improvement in the listener's performance in signal detection tasks as the bandwidth

and component density of the tonal complex is increased in remote critical bands (Bernstein & Green, 1987). These results have also been simulated in experiments using neural networks carried out in our laboratory (Howard, Harpster, & Miller, 1989).

Perhaps most exciting is new evidence reported by Berg and Green. Berg has developed a technique for estimating the subjective weights that a listener assigns to each component of a tonal complex (Berg, 1989; Berg & Green, 1990). A full discussion of this research is beyond the scope of the present report, however, two relevant issues will be highlighted.

First, Berg's findings have supported the empirical data gathered in previous profile analysis experiments, and has quantitatively shown that listeners do indeed assign relevance or salience weights to remote frequency regions of a broadband sound. This work seems particularly important and builds on the earlier work done by Gilkey and his associates (Gilkey, 1987). Second, there seem to be some interesting parallels between the recent work of Berg and his concept of human weights, and the weights derived from artificial neural network models.

A further distinction between profile analysis and pure-tone intensity discrimination is the memory process involved in the two types of tasks. Unlike the sensory representation of the stimulus believed to come into play with pure-tone intensity discrimination, the encoding of the stimulus in profile analysis is hypothesized to be a higher-order symbolic representation. This qualitative encoding of the stimulus has been characterized by Green as "signal like" or "not signal like" and is less susceptible to sensory decay over time.

Durlach & Braida (1969) have referred to this type of internal representation as "context coding." The sensory percept is transformed into a symbolic or categorical representation of sorts. The context-coding mode of memory suggests that a higher-level encoding of the stimulus occurs which is more robust, and is relatively immune to the effects of the interstimulus interval between the pair of auditory patterns presented to the listener. As Durlach and Braida have pointed out, "whereas in the trace mode the effects of the noise are dynamic and change with time, in the context mode the effects are independent of time" (Durlach & Braida, 1969; p. 374). This will be discussed in more detail in the following section.

To summarize, the optimal listening strategy in a psychoacoustic experiment will vary as a function of the demands of a given listening task. In profile analysis experiments the sound with the signal increment may have less overall energy than the comparison sound; hence a listening strategy which relies on computing the overall level of energy to detect the signal will be ineffective. The listener in a profile analysis task is forced to listen for a qualitative change in the shape or

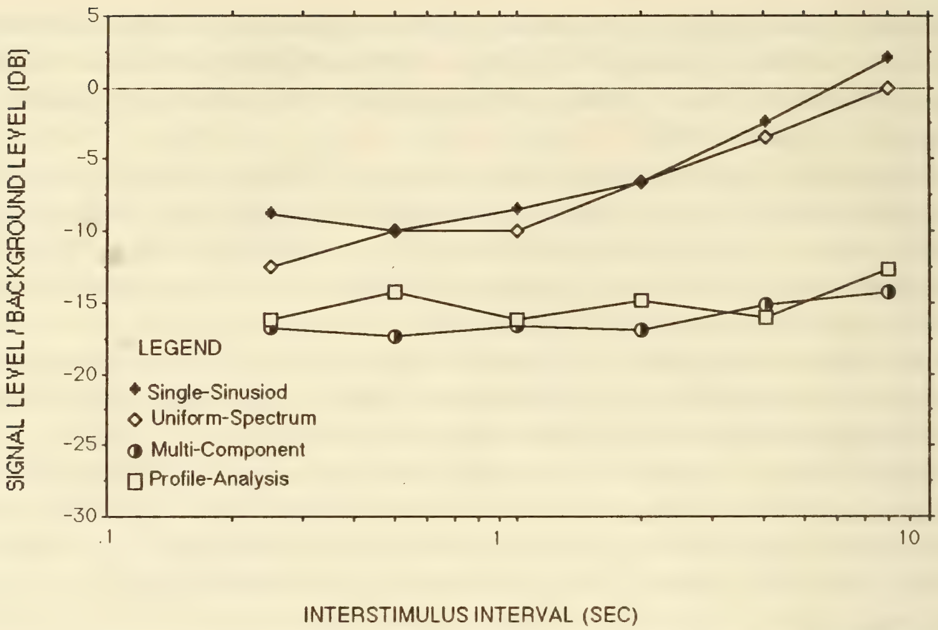


Fig. 4. Auditory discrimination under four conditions (Green et al., 1983). Value plotted along the ordinate is the signal level/background level required in order to discriminate 70.7% of the patterns correctly.

profile of the stimulus, as opposed to a quantitative change in the acoustic energy per se. In theory, well-trained listeners in a profile analysis task could listen to one interval and base their judgments on the presence or absence of a signal solely on this one sound. Unlike the traditional view of pure-tone intensity discrimination, which strictly emphasizes a narrowband energy detection mechanism, profile analysis emphasizes a broadband listening strategy which involves a simultaneous or global comparison of the frequency components within a single sound.

The Role of The Interstimulus Interval (ISI)

Figure 4 illustrates the results from the Green et al. study (1983) on the effect of the ISI in an auditory discrimination task. ISI is plotted against the signal-to-masker ratio required for a listener to perform at a 70.7% level of correct detection performance. The neural network simulations discussed below replicate the experiments discussed in the above study. Four simulations were conducted; two where only level cues were available, and two others where spectral shape information was also available.

The two upper curves of Figure 4 represent the conditions where no profile information is available to the listener. These were referred to earlier as the single-sinusoid and the uniform-spectrum conditions. In these conditions, as

the duration of the ISI was increased, listener performance on the task declined (as revealed by the higher signal levels that were needed to maintain the same level of correct performance). As the sensory traces of the signals in memory begin to decay, successive comparison of the traces becomes increasingly difficult.

The two lower curves represent the conditions where information on the spectral shape of the stimuli was available. These were referred to as the multi-component and the profile-analysis conditions. If the encoding of the stimuli is symbolic or qualitative as is proposed in a profile analysis task, then the duration of the ISI should have relatively little effect on listener performance, and indeed this is the case.

Of particular interest is the multi-component condition. In this situation the listener could have used a narrow band listening strategy to attend to the part of the spectrum where the signal is added and essentially listened for differences in the overall energy of the sounds. Or the listener could have used a broadband strategy and attended to other background components in the spectrum to analyze the shape of the sound. In this situation, it appears as if the latter strategy was chosen. As Green points out, "it means that for sounds of changing absolute level the ability to make simultaneous comparisons leads to better intensity discrimination than does successive comparison" (Green et al., 1983; p. 641).

Method

Four neural network simulations were carried out, each one replicating an experiment from the original Green et al. study. There were two stages involved in each simulation. In the first stage, each neural network was trained to perform a psychoacoustic task to a specified criterion in common use for this type of task. After each network had learned to perform the task, the connection weights were fixed so that they could not be modified during the testing phase. In the second stage, each network was tested with an adaptive psychophysical procedure (Levitt, 1971). The measurement used to judge performance was the ratio of the signal level relative to the masker level (SMR). Good performance is indicated by a low SMR (low threshold), where poorer performance is indicated by a higher SMR (higher threshold).

Stimulus encodings. All stimulus patterns presented to the network for training and testing were encoded as line spectra as illustrated in Figures 1 and 2. The stimuli were generated digitally, and the values encoded in each input vector corresponded to acoustic pressure in the psychoacoustic experiment we are modeling. A unique set of sound patterns was created for each of the four

network simulations, and 100 patterns were used per condition for training. Different sets of patterns were used for the training and testing phases.

In all of the conditions, except for the single-sinusoid condition, the stimuli consisted of 11 frequency components equally spaced from one another. The signal component was always an increment to the center frequency of the complex—except in the uniform-spectrum condition where all components were incremented equally. In the single-sinusoid condition the signal always consisted of an increment to a single frequency/masker component.

Auditory discrimination networks. The neural network used in each simulation was a two-layer, fully-interconnected, feed-forward artificial neural network trained with a back-propagation algorithm. There were twenty-two input units[1] and one non-linear output unit as shown in Figure 1b. The values of the stimulus patterns encoded in the input vector are clamped to the nodes in the input layer. The output unit is non-linear, and its transfer function corresponds to a sigmoid.

Each sound pattern was encoded as an input vector. Each input vector consisted of 23 elements,[2] encoding the stimuli from the first and second intervals, plus a single target value. The first 11 values in each vector encoded the first sound, and the second 11 values encoded the second sound. The target value was either 0.01 or 0.99. A value of 0.01 indicated that the signal occurred in the first interval, and a value of 0.99 indicated that the signal occurred in the second interval. All input vectors were sampled from the full set of vectors, and randomly presented to the network during training.

Decay function. Since the neural networks used in this study have no explicit means for representing time, the decay associated with increasing ISI durations was simulated as follows. Sensory decay was modeled by differentially incrementing the values of the weights taken from the networks which were trained and had converged on a solution. Each weight from a particular network was divided by the same value or constant. The function relating ISI to the value of the divisor is shown in Figure 5. The smaller the value of the divisor, the greater the simulated ISI. The rationale for this approach is the belief that sensory decay relates to some weakening or decrement of a sensory response to a physical event.

During the testing phase, the asymptotic weight matrices were tested at 6 different divisor constant or scaling levels ranging from 0.89 to 0.60. Twenty

[1] Except for the single-sinusoid network where there were only two input units.

[2] Again, the single-sinusoid network was an exception. In this case each input vector consisted of three elements, the value of the two frequency components, plus a target value.

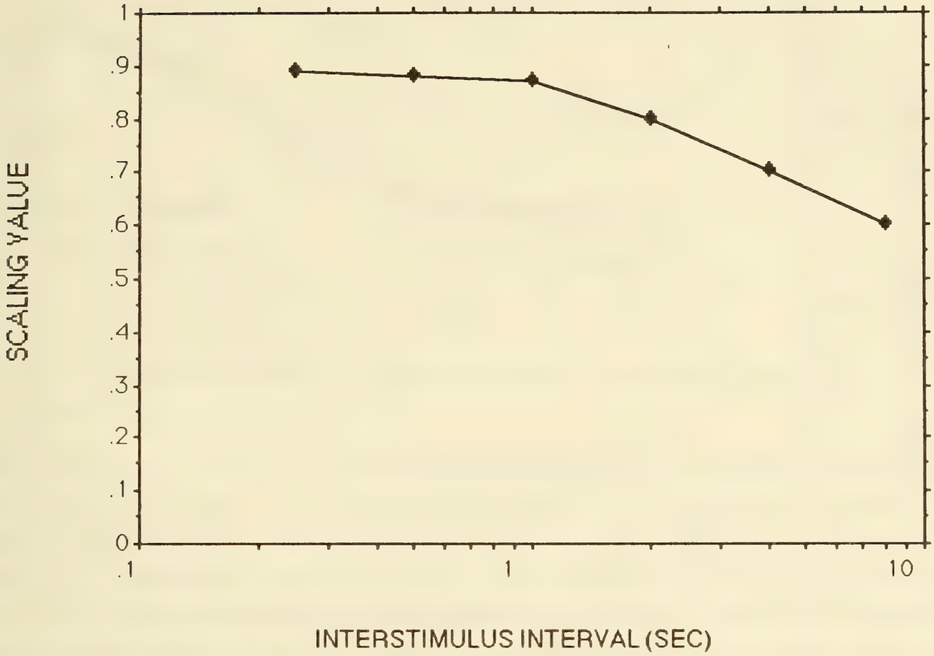


Fig. 5. Decay function relating ISI to a scaling constant.

psychophysical adaptation runs were performed at each constant level and an average of the twenty values was taken.

Results and Discussion

The psychophysical adaptation curves from each of the four computer simulations are plotted in Figure 6. In each of the four computer simulations, the networks learned to perform the task without difficulty. In general, the simulation data fit the human data (Figure 4). This holds for both the shapes of the curves as well as their absolute dB levels. The one exception to this is the multicomponent condition.

In the two conditions where a successive energy comparison is the only strategy available to detect the signal (single-sinusoid and uniform-spectrum conditions), discrimination performance declined as ISI increased. In contrast, for the condition in which a simultaneous, broadband spectral comparison was required (profile-analysis condition), discrimination performance was relatively constant, independent of ISI. In all three of the above conditions the network's performance mimics the performance of human listeners.

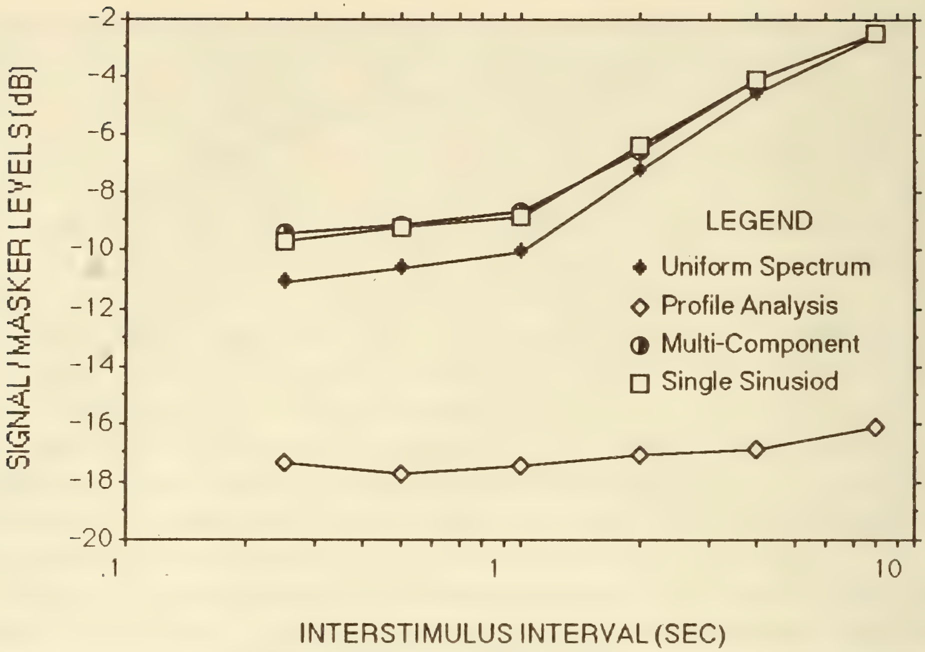


Fig. 6. Discrimination thresholds obtained from neural network simulations that varied ISI (scaling values) for each of the four experimental conditions.

In the multi-component condition, the network's performance diverged from the human data. Unlike the profile-analysis condition, performance declined as the ISI was increased. In this condition, either of two listening strategies are effective for performing the task: a successive comparison across intervals, or a simultaneous comparison within an interval. While it can be inferred from the psychoacoustic data that the human uses the latter strategy, the neural network model used the former. What can account for this difference? This will be discussed in the next section.

Analysis of Asymptotic Weights

Next, an analysis of the asymptotic weight matrices was performed. By examining the pattern of weights from each network after it has been trained, insights can be drawn into how each network performed the discrimination task. It was observed that in all cases the strongest connection weights were from the input units where the signal component was clamped. Conclusions about the attentional aspects of the neural networks and the type of listening strategies which were used will be discussed.

Single-sinusoid network. Figure 7 illustrates the weights for the network trained in the single sinusoid condition. There are three values shown, one for

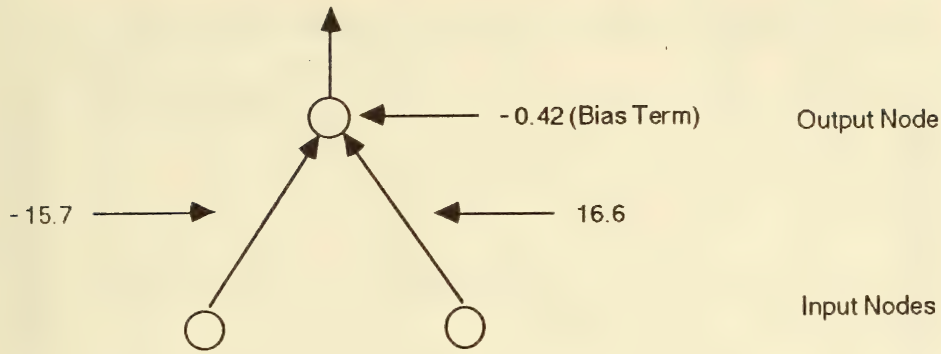


Fig. 7. Asymptotic weights from a neural network trained in the single-sinusoid condition.

each input node, plus a bias term for the output node. The values of the weights were: left input node = −15.7, right input node = 16.6, bias term = −0.42. The opposite but equivalent magnitudes of the two input weights, with a bias value close to 0.5, suggests two points. First, it's clear that both units were used by the network in performing the discrimination task. This is due to the non-zero weights assigned to each node.[3] Second, the bias value indicates that the network was equally likely to respond to a signal either on the left or the right side of the input vector.

Uniform-spectrum network. Figure 8 plots the magnitude of the weights for the 22 input nodes for the uniform-spectrum condition. There are two important observations. First, as indicated by the non-zero weights in both intervals, the network used a successive comparison strategy to compute the difference in energy between the sounds processed at separate intervals. This successive comparison strategy is consistent with human auditory discrimination data. Second, the entire frequency spectrum was attended to by the network. In other words, the network used a broad-band strategy to select its response, and attended to all channels where energy was present.

The discrimination thresholds for human listeners are no better in the uniform-spectrum condition than in the sinusoidal condition. It appears that human listeners were using narrowband listening strategy. This may have occurred for two reasons.

The first possibility is that by attending to only a narrow bandwidth of energy, less attentional effort is required of the listener to perform the task. Clearly, any single channel attended to in each sound is sufficient for making a decision. A second possibility is due to internal noise which is correlated across channels in

[3] It is not important if the weights are negative values in order to assess the contribution of an individual unit to the overall decision arrived at by the network. The absolute value of the weight is what counts.

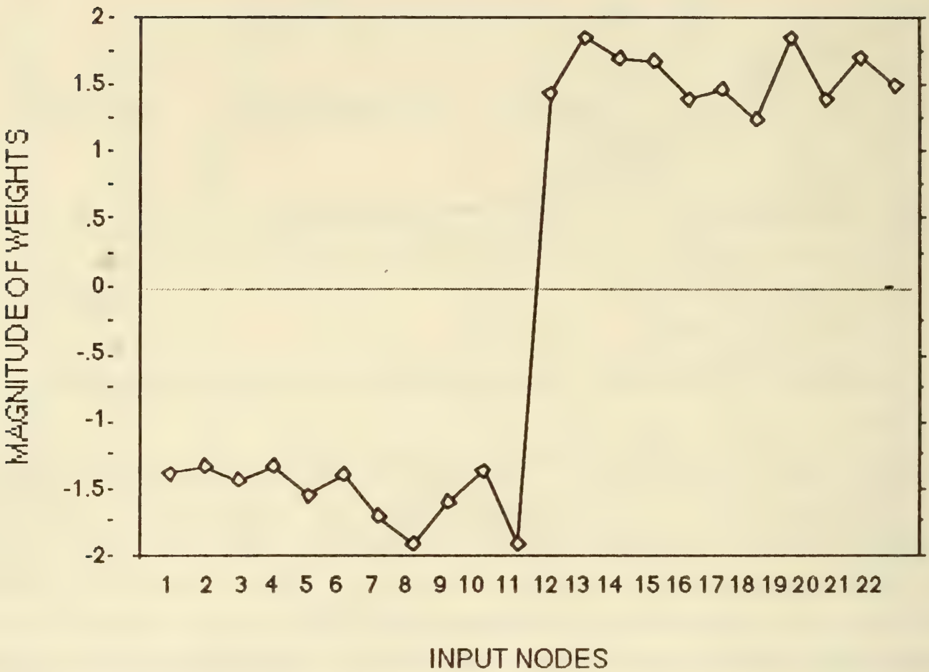


Fig. 8. Asymptotic weights from a neural network trained in the uniform-spectrum condition.

the auditory periphery. The advantage of monitoring more than a single channel is minimized, so the listener locks into a single band.

The network on the other hand is adjusting its weights in response to anything which correlates with the response (i.e., the presence of the signal). Since each masker component was incremented by a constant signal amount, all input nodes contained information which correlated with the signal and provided reliable data which are used by the network. This explains the 1.5 dB improvement in performance seen (Figure 6) with the network trained in the uniform-spectrum condition as contrasted with the networks which had a signal increment added to only a single component.

Profile-analysis network. Figure 9 plots the weights from the network trained in the profile-analysis condition. As can be seen, the weight of the input unit centered at the signal frequency is largest in magnitude, while the weights of the nodes clamped to the masker components are relatively small non-zero values. This indicates that the principal comparison which is occurring is within each interval, where the signal component is being compared with the maskers. As in the uniform-spectrum condition, the network used a broad band comparison strategy to perform the task. Unlike the previous condition, the network is computing a function which determines the difference between the value of the signal component against the sum of the masker values. This is entirely consistent with the human data which argue for a simultaneous comparison in a

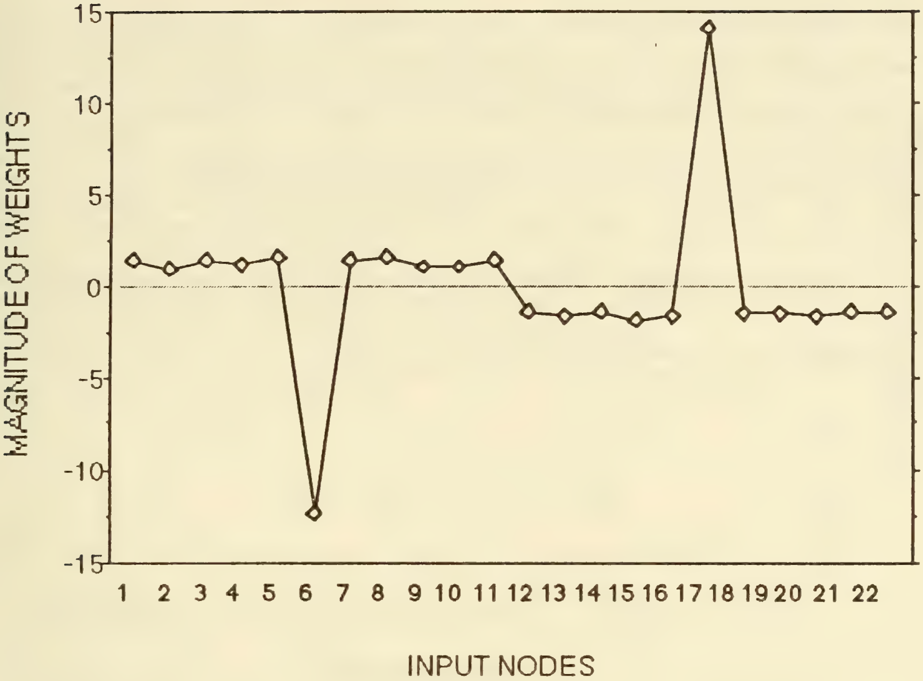


Fig. 9. Asymptotic weights from neural network trained in the profile-analysis condition.

profile analysis task. Further, the network's performance with larger ISI's supports the view of a more robust internal representation of the stimulus which is less sensitive to sensory decay over time.

Multi-component weight matrix. Figure 10 plots the weights from the multi-component condition. As above, the magnitudes of the weights from the input unit centered at the signal frequency is largest in magnitude. However, unlike the above network trained in the profile condition, the values of the weights clamped to the nodes for the masker components are all zero. This explains the performance decrement observed in Figure 6 for this condition. It appears that the network was performing narrowband listening, and successively comparing energy across intervals of a trial.

This result is inconsistent with Green's inference that in the case of profile analysis, a simultaneous or successive comparison may be possible, but that a simultaneous comparison within a sound is more likely. In this situation, the network could have performed a simultaneous comparison of the components within an interval, but did not.[4]

[4] In other simulations carried out in our laboratory using multi-layer feed-forward networks with a single hidden layer, the performance of the network trained in this condition was very similar to the profile-analysis network. Another distinction involved the decay function. Time or sensory decay was modeled by adding Gaussian noise with zero mean and different standard deviations.

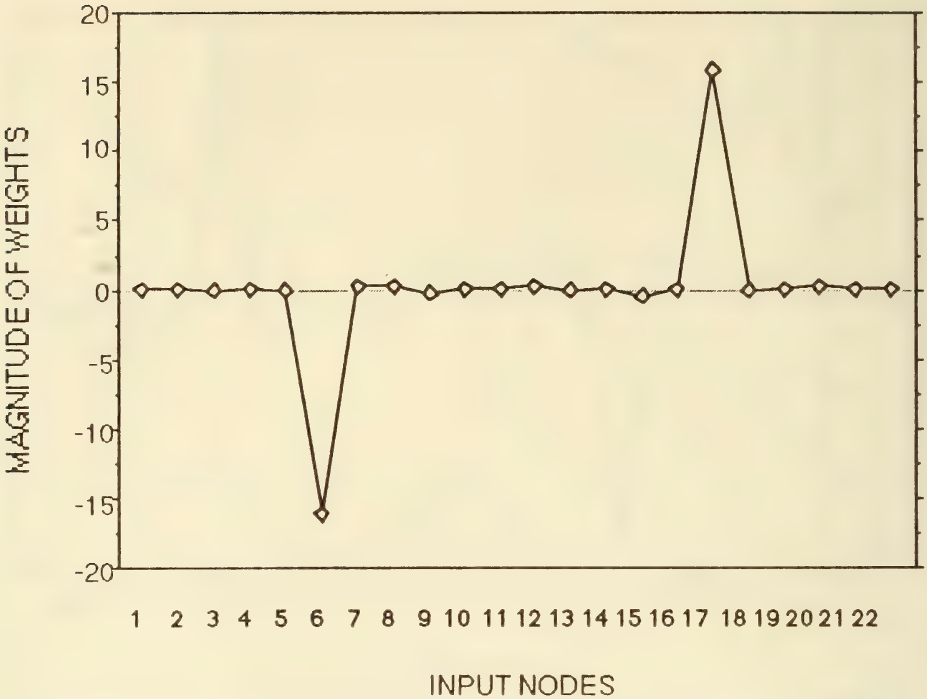


Fig. 10. Plot of asymptotic weights from neural network trained in the multi-component condition.

Conclusions

The purpose of the computer simulations carried out in this study was to understand the psychological phenomena of intensity perception and auditory profile analysis. These studies have shown that neural networks can be a useful tool for modeling and evaluating the existing body of psychoacoustic data. Further insights into the more cognitive aspects of auditory perception were discovered. These included both the listening strategies as well as attentional issues involved in auditory processing.

Acknowledgements

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Evaluation of St. Lucia's Geothermal Resource

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ABSTRACT

The Caribbean island of St. Lucia has a strong geothermal energy resource. Under USAID funds, the Los Alamos National Laboratory made measurements of St. Lucia's geothermal field and conducted an engineering and economic evaluation of its potential for meeting electricity and industrial process heat needs of St. Lucia. This paper, presented at a 1984 international energy conference in Caracas, Venezuela, summarizes the Los Alamos study and its recommendations for development of St. Lucia's geothermal resource. Subsequent drillings of geothermal wells at St. Lucia under United Nations funding have confirmed the Los Alamos geotechnical measurements. St. Lucia's negotiations with several private firms for developing the geothermal field and associated electrical and process heat plants have not yet produced agreement to undertake the work.

Introduction

St. Lucia is a volcanic island on the eastern rim of the Caribbean Sea. The southwestern portion of the island is dominated by mountainous terrain, with steam fumaroles and boiling pools attesting to its volcanic origin. The last volcanic eruption probably occurred about 20,000 years ago, and geologic and geophysical studies suggest the presence of a large geothermal resource beneath the Qualibou Caldera. British geologists explored this resource and drilled seven shallow wells in 1970. Four of these wells encountered steam in limited quanti-

* This work was performed under the auspices of the U. S. Department of Energy.

ties. A subsequent Italian assessment concluded that development of St. Lucia's geothermal resource is probably economically feasible.

In 1983, the Government of St. Lucia commissioned the Los Alamos National Laboratory to conduct a study of the possibilities for generating electricity and industrial process heat from the geothermal resource beneath the Qualibou Caldera. In April 1984, Los Alamos reported to the Prime Minister of St. Lucia that new measurements and analysis of available data now justify beginning the drilling phase of a program to develop the full geothermal potential of St. Lucia.

This report summarizes results of the Los Alamos assessment of St. Lucia's geothermal resource, and it discusses possibilities for generating electricity and process heat, both for existing St. Lucian industries as well as for new industries which cheap energy might attract.

The work performed for this study was funded by the Trade and Development Program of the United States Government.

Geology and Geophysics

St. Lucia is a former British colony which is now an independent member of the British Commonwealth. An island nation in the eastern Caribbean Sea, it is located at 61° west longitude and 14° north latitude. The island is approximately 25 miles long and has a maximum width of 15 miles. St. Lucia covers an area of 238 square miles and had a population in 1981 of 122,000 persons.

Geology

St. Lucia has a volcanic geology, and the Qualibou Caldera near Soufriere in the southwest exhibits many of the characteristics of an underlying geothermal resource (Figure 1). This caldera, first identified in 1964 during detailed geologic mapping, is estimated to be between 40,000 and 300,000 years old. The geothermal aspects of the area have long been recognized in the Sulphur Springs and the nearby hot springs, which have been used for mineral baths at least since the early European settlement in the 17th century. More recent investigations have resulted in new geologic and economic studies of the Sulphur Springs area which describe a steam-rich geothermal system within a relatively shallow reservoir.

The volcanic events which formed St. Lucia are estimated to have occurred approximately one million years ago. The most spectacular volcanic domes of that period of activity are the plug-domes known as Petit Piton and Gros Piton, dated at 250,000 years. The Pitons are located along the western side of the caldera.

Two major northeast-southwest faults straddle the Qualibou Caldera. There are also minor southeast-northwest faults. Faulting has controlled, for the most

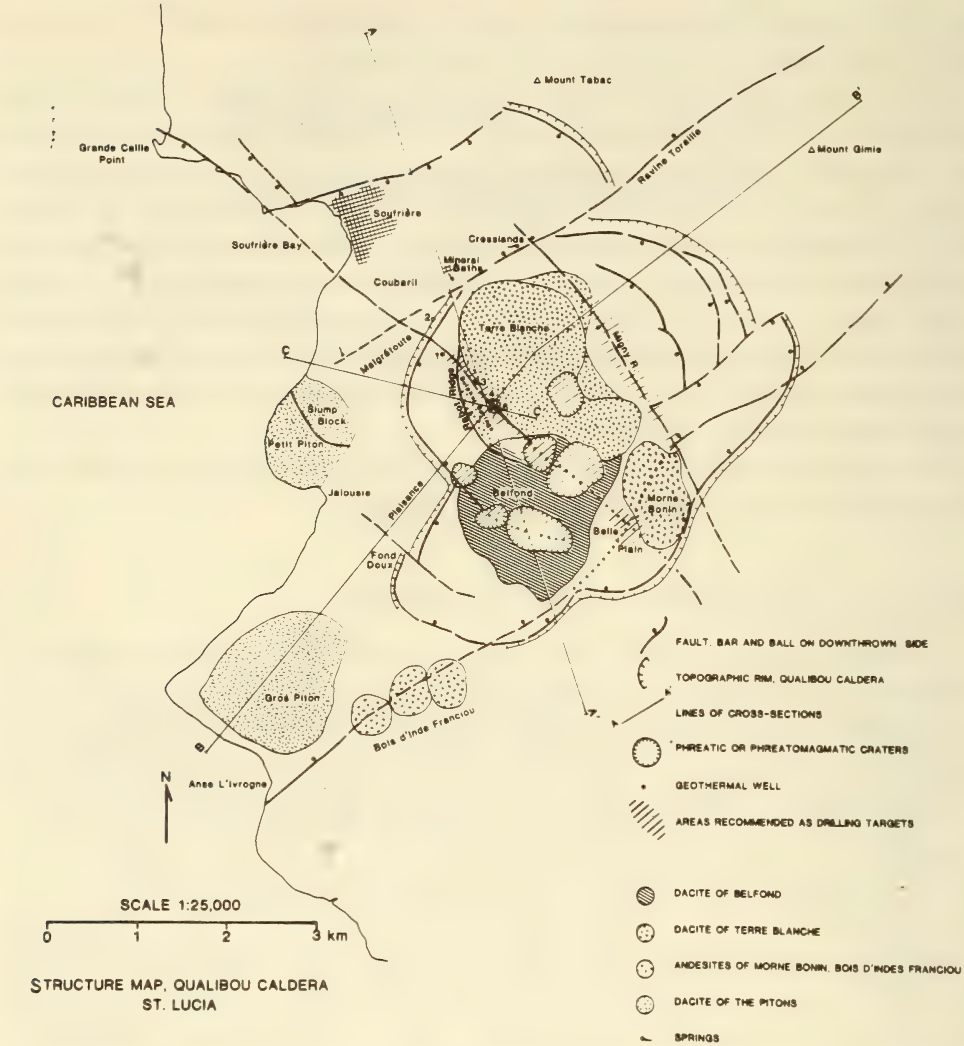

Fig. 1. Structural map of the Qualibou caldera showing regional NE-SW and NW-SE linear faults and curvilinear caldera faults. The last eruptive units are shown by the dacites of Belfond and Terre Blanche.

part, the location of thermal springs. Regional faults and caldera faults are important in providing pathways to the surface for thermal waters.

The Qualibou Caldera appears to be over a magma body or bodies located at a depth of three to four kilometers. The temperature gradient of 220° C per km measured in wells drilled by the British (numbered vertical lines on Figure 2) suggest temperatures higher than 600° C at a depth of 3 km. Geothermal fluids and vapors should be found at a depth of 1 to 2 km under the entire caldera area and in abundance where permeable rocks allow for greater fluid movement.

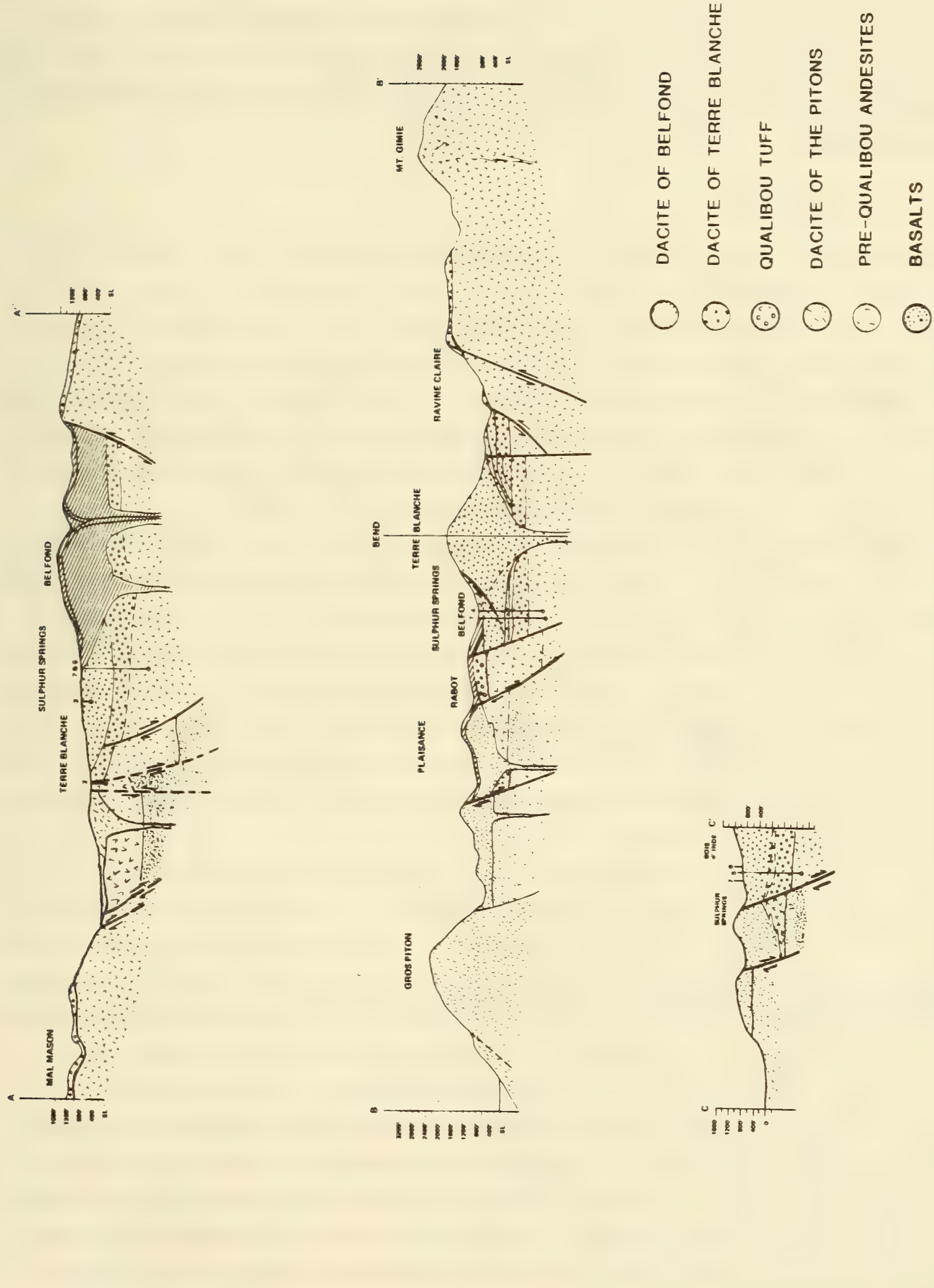

Fig. 2. Geologic cross-sections of the Qualibou caldera: A–A′ is NNW–SSE, B–B′ is NE–SW with a bend at Terre Blanche, and C–C′ is E–W on the western side of the caldera.

Geotechnical Measurements

Quantitative assessment of a geothermal resource requires geotechnical measurements and analysis to provide confidence in estimates of fluid temperatures and of the precise location of promising subterranean regions. Two proven techniques for acquiring such data are measurement of the electrical resistivity of the soil and the chemical analysis of samples of steam or fluid from the suspected geothermal regions. The Los Alamos investigation employed both of these techniques.

Electrical Resistivity

Direct current (DC) electrical resistivity methods have been employed for geothermal exploration in many countries and have proven to be a valuable adjunct to the drilling of shallow and deep holes. Numerous case studies indicate that high quality (greater than 200° C), liquid dominated geothermal reservoirs are characterized by resistivities of less than 10 ohm-meters (o-m) This has been proven true regardless of the resistivity of the host rock, which may be typically in the range from 100 to 1000 o-m. Rocks such as granite, basalt, limestone and sandstone have essentially infinite resistivity at 450 to 500° C.

Shallow resistivity measurements had been made in the Qualibou Caldera region prior to the Los Alamos effort. The earlier studies developed resistivity profiles throughout the region to a maximum depth of 700 m. Low resistivity values were found in the vicinity of Soufriere and nearby points generally to the north of Sulphur Springs. Additional lows were centered in the south near Etangs. Resistivity highs were associated with the Belfond area and beneath Sulphur Springs at depths below 600 m. The low values are associated with the geothermal system, while the higher values measured beneath Sulphur Springs may be due to a steam zone.

After evaluating all available data, Los Alamos geophysicists ran a 5.2 km, north-south trending resistivity profile (Figure 3). A nominal dipole length of 200 m was selected to obtain high resolution data from the survey, which contained a total of 32 electrode stations. In order to obtain resistivity measurements to a depth of 2 km, the Los Alamos team used a 35 kilowatt DC transmitter capable of generating currents up to 80 amperes from up to 438 volts.

The resistivity data from the dipole soundings are plotted as a function of depth in Figure 4. These data are consistent with the shallow resistivity measurements made during earlier investigations. The regions containing material of less than 10 o-m most probably contain hot brines. The zone beneath Etangs, containing material of less than 1 o-m, may contain hot water rising along a fault. The deep high resistivity zone beneath Sulphur Springs can be reasonably

Fig. 3. Location of the 5.2 km-long resistivity profile line across the Qualibou Caldera containing a total of 32 electrode stations.

interpreted in two ways. The first is that the high resistivity layer is due to a very hot, dry steam field. The second interpretation is that the higher resistivity indicates the presence there of less permeable rock. This would suggest that the region of low resistivity between Belfond and Sulphur Springs represents a fault along which thermal fluids are rising and moving from south to north, emerging at Sulphur Springs.

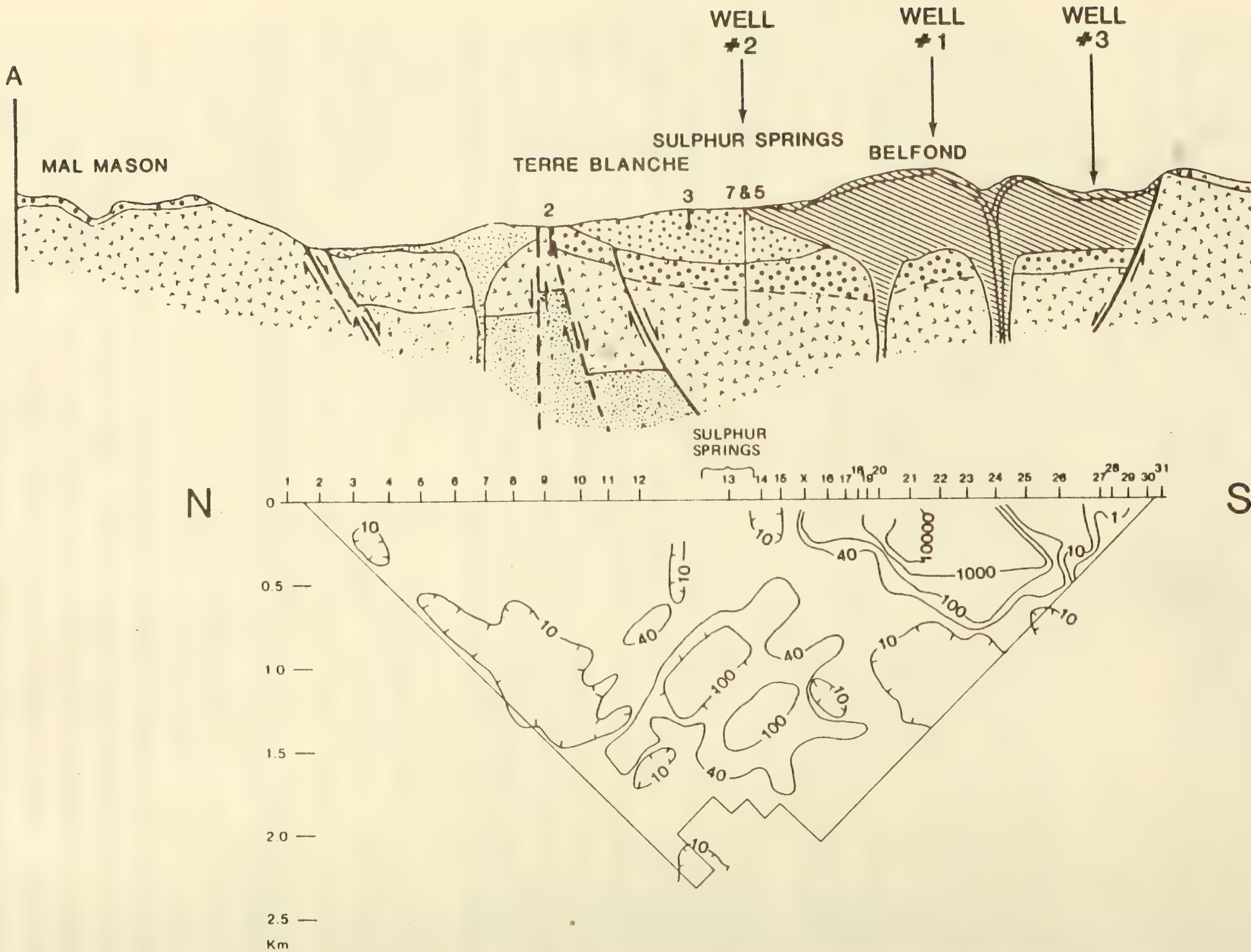

Fig. 4. Resistivity data from the dipole-dipole survey plotted as a function of depth. Resistivity values are in ohm-meters and are shown beneath the appropriate geologic cross section.

Hydrogeochemistry

The first comprehensive geochemical studies of the Sulphur Springs area of the Qualibou Caldera were done during the British geothermal drilling effort in 1970. Data on outlying springs were reported recently by the Italian firm, Aquater. Los Alamos geochemists augmented this earlier work by obtaining and analyzing fluid samples from outlying hot springs and cold waters within the caldera and from numerous sources in the Sulphur Springs area.

The most common thermal features are broad pools or caldrons filled with fountaining muddy water. The lavas are altered to clay. Sulphur, gypsum and pyrite are concentrated near fumaroles and steaming ground, while iron oxides stain the surrounding rocks to various hues of red and orange.

Hot spring waters at Sulphur Springs display chemical characteristics common to acid-sulfate systems. Acid-sulfate water does not necessarily indicate that a steam-dominated system lies at depth. The available drilling data indicate variable conditions in the steam zone beneath Sulphur Springs. Temperatures approach 220° C and pressures are less than 444 pounds per square inch (psi), which suggest a steam-dominated zone beneath Sulphur Springs. The British well #4 alternately produced geothermal brine and steam. Chemical analysis of that brine showed wide variations of concentrations of elements but essentially constant ratios of certain elements. This indicates steam loss from brine in a fracture system of limited volume.

Analysis of available data points to extremely high temperatures beneath Sulphur Springs. The three best indicators are:

—Stable isotopes of water, where the brine shows deuterium and oxygen compositions that indicate extensive exchange of oxygen between water and rock in the reservoir. The pronounced "shift" in the measured isotopic oxygen composition is a characteristic observed of deep reservoir fluids with temperatures in excess of 250° C.

—Brine chemical analyses (Table 1), which point to Sulphur Springs having a consistent subsurface reservoir temperature of 280° C.

—Temperature of vapors from superheated fumaroles (171° C), which calculates isentropically to 260° C at the source depth.

Table 1.—Gas Temperature Indicators, Sulphur Springs

Brine components	Bubbling Pool 72° C (161° F)	Superheated Vent 171° C (340° F)
H_2 (vol-%)	5.04	5.63
O_2	0.02	0.54
N_2	1.11	2.51
CH_4	0.64	0.69
H_2S	1.67	1.09
CO_2	91.93	89.59
Total	100.4	100.1
Gas geothermometer	283° C (541° F)	280° C (536° F)

Summary

The Los Alamos analysis of the deep resistivity and geochemical measurements supports a recommendation to drill geothermal wells at the following locations (Figure 4):

—The craters of Belfond, which could determine if the main area of geothermal upflow is centered within the area of youngest volcanism. This well is expected to encounter dry rocks to a depth of 600 to 900 m, below which geothermal brine is expected.
—The valley of Sulphur Springs, near the British wells #4 and #7, but targeted for a depth of 2 km to pass through the shallow vapor zone and penetrate the postulated deep brine reservoir. This well is expected to encounter very hot, dry steam between 600 and 1700 m and a geothermal brine at approximately 1800 m. It is also possible that a less permeable fluid bearing rock will be encountered instead of the steam zone.
—The Etangs area, south of the road near the Nutmeg Bar. This well should pass through the southern caldera-bounding fault and is expected to encounter geothermal fluids as shallow as 1000 m.

Applications of St. Lucian Geothermal Energy

The heat energy produced by geothermal wells in St. Lucia could be converted to electricity or industrial grade process heat by heat exchangers and steam turbines of proven design similar to those now in use in many countries. In the following sections the current and projected demand for electricity and industrial process heat on St. Lucia, and concepts and budgetary cost estimates for meeting those demands with geothermal energy from wells near Sulphur Springs are described. The costs of generating electricity and process heat from the St. Lucian geothermal source are compared with costs of energy generated from other heat sources, such as fuel oil, wood and coal. The possibilities for using geothermal heat in some existing St. Lucian industries are discussed and some new industries which might be attracted to St. Lucia by the availability of cheap energy described. Finally, a discussion is provided on the possible impact on the economy of St. Lucia which could result from the development of its geothermal resources.

Electricity

Electricity on St. Lucia is now generated by St. Lucia Electricity Services Limited (LUCELEC), using large, British, low speed diesel engine generators. A total of approximately 16 megawatts (MW) is installed in two stations: one in the north near the capital, Castries, and the second near the southern city of Vieux Fort. Two separate, 11 kilovolt (KV) transmission grids serve LUCELEC's 14,814 domestic and industrial customers in the northern and southern regions of the island. Plans exist to replace these two grids with a single, inte-

grated, 66 KV grid in the near future in order to reduce the excessive transmission losses being experienced with the current system.

LUCELEC projects a continuation of current demand growth of 5% per year in the northern region and 4% per year in the south. Figure 5 shows the 1983 installed capacity (16 MW), peak power consumption (12 MW) and average power consumption (8 MW), and it plots the LUCELEC projection of annual growth in power demand, which they assume will continue to grow at the same rate through the year 2016. Figure 5 also reflects the 4 MW reserve capacity currently in the system and projects increasing the reserve at the assumed demand growth rate until a 5 MW reserve capacity is achieved. A 5 MW reserve capacity is then assumed for the remainder of the period studied. To maintain that level of reserve capacity, LUCELEC must add new capacity soon, and the

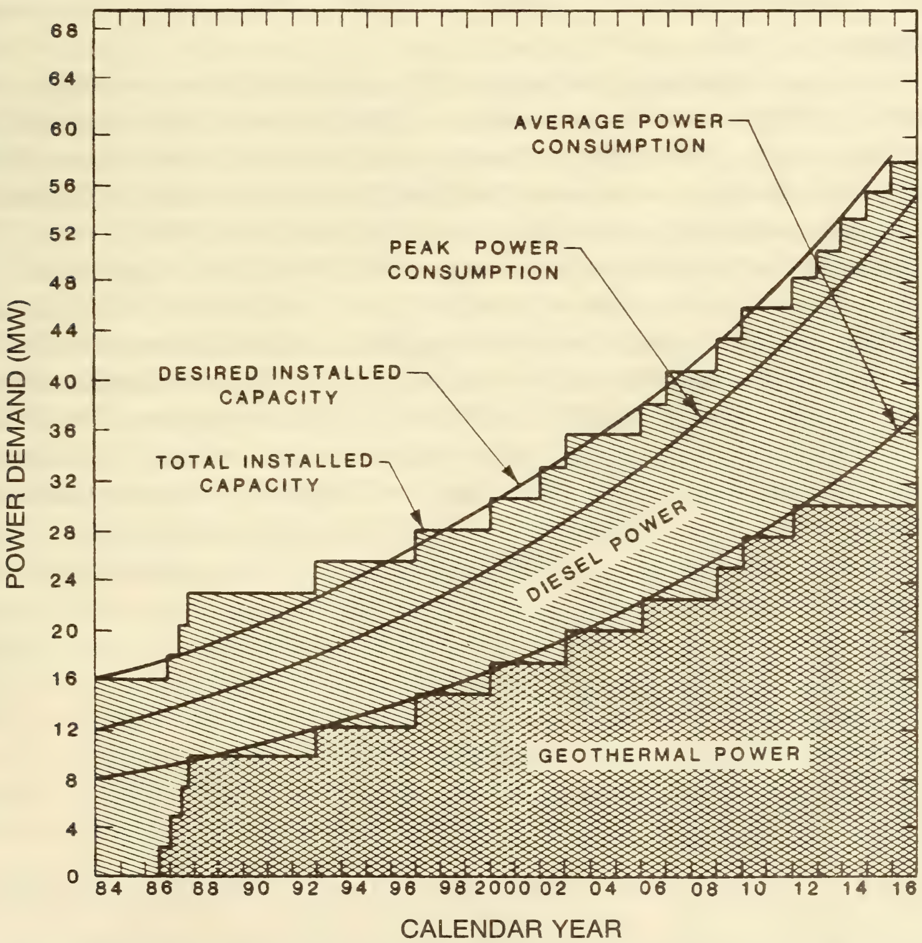

Fig. 5. Geothermal electric power demand in St. Lucia for 1983 (actual) through 2016 (estimated).

total new capacity required to meet new demand will be approximately 10 MW by 1996 and approximately 32 MW more by the year 2016. Figure 5 shows 10 MW of geothermal power coming on line during 1986–88 and 20 MW more during 1992 through 2011.

The geothermal system assumed for generating electricity on St. Lucia consists of a field of production wells, each producing brine at 250° C and with an assumed flow of 270,000 pounds per hour. The 50,000 pounds of steam per hour required to drive a 2.5 MW, well-head steam turbine-generator would be flashed from the brine in a steam separator, leaving residual heat totalling approximately 44 million BTU's per hour in the brine. This waste heat can be used for industrial process heat applications, as will be discussed later. Typical turbine designs have an inlet steam pressure of 75 pounds/in^2 in absolute units (psia) and a back pressure of 3 in. of mercury (1.5 psia). Steam condenser cooling can be by air flow in a cooling tower or by cooling water, perhaps using sea water.

This modular approach of adding one 2.5 megawatts of power available to the electrical grid (MWe) of the geothermal well and one steam turbine-generating set at a time to the LUCELEC grid permits the geothermal system to operate at near rated capacity for maximum economy. It also permits using the existing diesels for standby and peaking operation and thus allows them to remain in service longer before reaching their design life of 100,000 hr. of operation.

Using the planning schedule reflected in Figure 5, estimates of the capital and operating expenditures which would be required over that 33-year period were developed. Costs were itemized by year and a discounted cash-flow computer code calculated the Levelized Life Cycle Cost (LLCC) for the system. The LLCC is the unit cost of electricity in dollars per kilowatt-hour which, if charged to consumers throughout the life of the plant, would result in revenues equal to the total capital and operating costs of the plant during that same period.

The major assumptions on which our estimate of the capital cost of the geothermal electric power system are based were:

(a) Values in 1983 \$(US)
(b) LUCELEC power demand projection
(c) BUSBAR cost for electricity
(d) Integrated grid of geothermal and diesel power
(e) 30 yr. of operation
(f) 30 MW of geothermal power
(g) \$(EC) = \$(US) × 2.7

The well-head steam-turbine system is of a type currently available from several U.S. competitors. A set rated at 2.5 MW can be skid-mounted and moved over rough terrain to the well-head. Such equipment has a design life of 30 yr. and can

be purchased in the U.S., shipped to St. Lucia and installed, all for approximately \$1000 (US) per kilowatt (\$2700 (EC)/KW). The production wells are assumed to require drilling to a depth of 2000 m and to produce brine or steam with a wellhead temperature of 250° C. Each well is assumed to cost \$2 million US (\$5.4 million EC). A 50% success ratio for bringing in producing wells, each of which will have a 20 yr. life, is also assumed.

In calculating operating costs, all funds were borrowed at 10.5% interest and inflation was assumed to be at a constant 5% annual rate throughout the period being considered. Well maintenance would be 10% of the initial well cost and generator maintenance would be 2% of the initial cost. A three-shift operation with a ten-person crew plus three supervisors per shift totals to an annual cost of \$540,000 (EC) per yr. Additional wells would have to be drilled and additional well-head steam turbine-generators added as needed, at the costs cited above. In view of the preliminary nature of the system design and the uncertainties associated with a new venture of this type in St. Lucia, 25% was added for contingencies to the estimates of both initial capital costs and annual operating costs.

Using these assumptions, a LLCC was estimated at \$0.17 (EC)/KWh (\$0.063 US) for the geothermal steam turbine-generator system. The corresponding cost of electricity produced by the existing diesel system was calculated to be \$0.243 (EC)/KWh (\$0.09 US). The cost of producing the much smaller amounts of peaking power by the diesel system is slightly higher, or \$0.275 (EC)/KWh (\$0.102 US).

Figure 6 compares the LLCC of geothermal and diesel power with the costs calculated for modern steam plants fueled by imported Bunker C fuel oil and by Illinois No. 6 coal shipped from the Gulf Coast of the U.S. The conclusion to be drawn from Figure 6 is that, even with the very conservative capital and operating costs assumed for the geothermal system, it offers over 30% cost savings compared to the existing system and is also significantly cheaper than electricity from new coal- or oil-fired steam plants. However, electricity costs of 6 US cents per kilowatt-hour are not low enough to attract such energy-intensive industries as aluminum smelting, which are able to buy electricity from large power plants in the U.S. for 3 to 4 cents per kilowatt-hour. Nevertheless, the 30 MW geothermal system assumed here for St. Lucia would result in a reduction of oil imports totalling 231 million gallons over 30 yr. The difference in cost between all-diesel generation and geothermal base-load plus diesel peaking indicates a saving of \$250 million (EC) over that 30-yr. period.

Industrial Process Heat

The heat available from the St. Lucian geothermal resource can be converted to a form useful for industrial processes in two ways: (1) direct heat transfer at

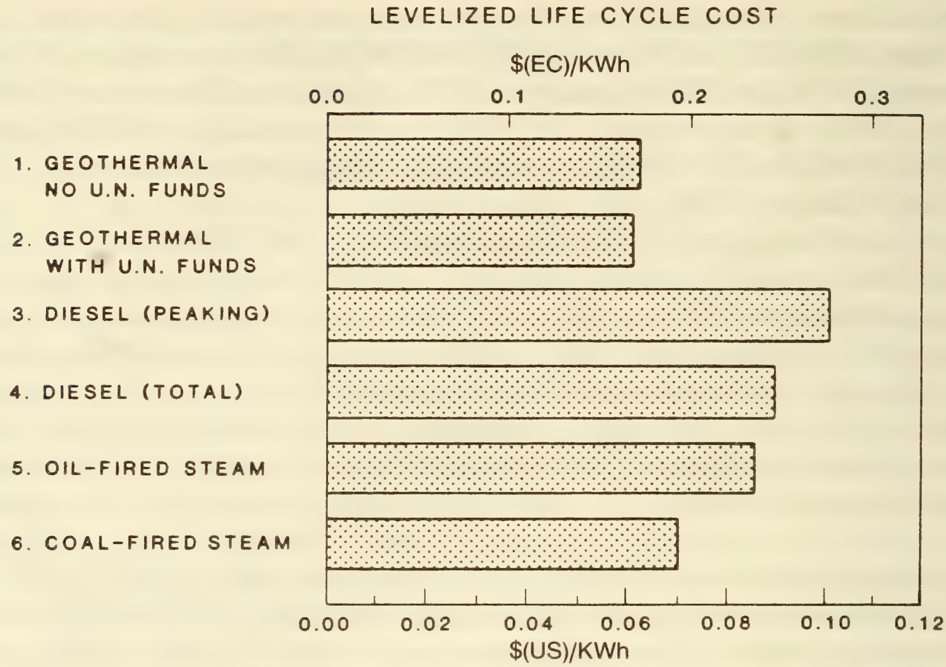

Fig. 6. Cost comparison of electricity from geothermal generation and from alternative technologies.

the well-head to a pressurized hot water loop, or (2) capture of heat in the residual brine from the steam separator in the power generation system.

The direct transfer of heat from the base-case well assumed for a 2.5 MW turbine-generator could be used instead to deliver over 95 million BTU's per hr. in water heated to 222° C (433° F) to industrial plants requiring process heat and located within two miles of the well. For more distant plants, the delivered temperature would be slightly lower. Using waste heat from the power generation process, approximately half that heat flow at a lower temperature of 140° C (285° F) could be delivered to the same plants.

Figure 7 indicates the comparative costs of process heat from the geothermal heat source in St. Lucia with costs from Bunker-C fuel oil in St. Lucia and with oil and natural gas in the U.S. The upper range of costs for the St. Lucian geothermal case (approximately \$3.7 (US) per million BTU) is less than half the cost of process heat derived from Bunker-C fuel in a modern boiler in St. Lucia. The lower range of St. Lucian geothermal process heat costs (approximately \$0.8 (US) per million BTU) is less than one tenth of the St. Lucian Bunker-C case.

The principal factors causing the wide range of costs of geothermally produced process heat for industrial applications are the temperature required at the factory, the distance of the factory from the geothermal plant, the plant's

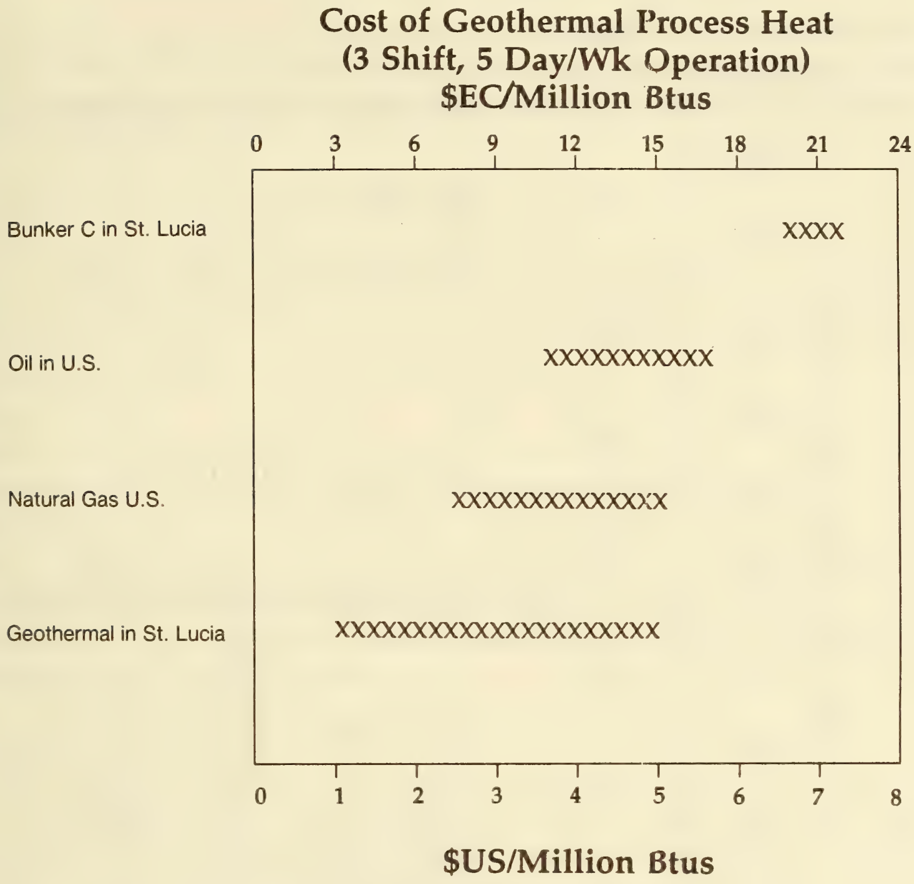

Fig. 7. Process-heat cost comparisons in St. Lucia.

operational plan (numbers of shifts per day and days per week), and the percentage of available heat per well delivered to the factory. Figure 8 reflects these variables, with the lowest cost being for 140° C (285° F) heat delivered to a plant operating 3 shifts per day, 7 days per week, located 2.4 km from the well-head and using all the heat available from the supplying well. The highest cost of geothermal process heat shown (or over four times the lowest cost) is for 222° C (433° F) heat delivered to a plant operating 5 days per week and using only 10% of the heat available from the well. Figure 8 also shows, as did Figure 7, that the cost of Bunker-C heat in St. Lucia is over twice the cost of the costliest geothermal process heat.

The conclusion to be drawn from these estimates is that industrial process heat from the St. Lucian geothermal resource promises to be so cheap that existing industries would probably switch to geothermal heat and new industries would be attracted to the island.

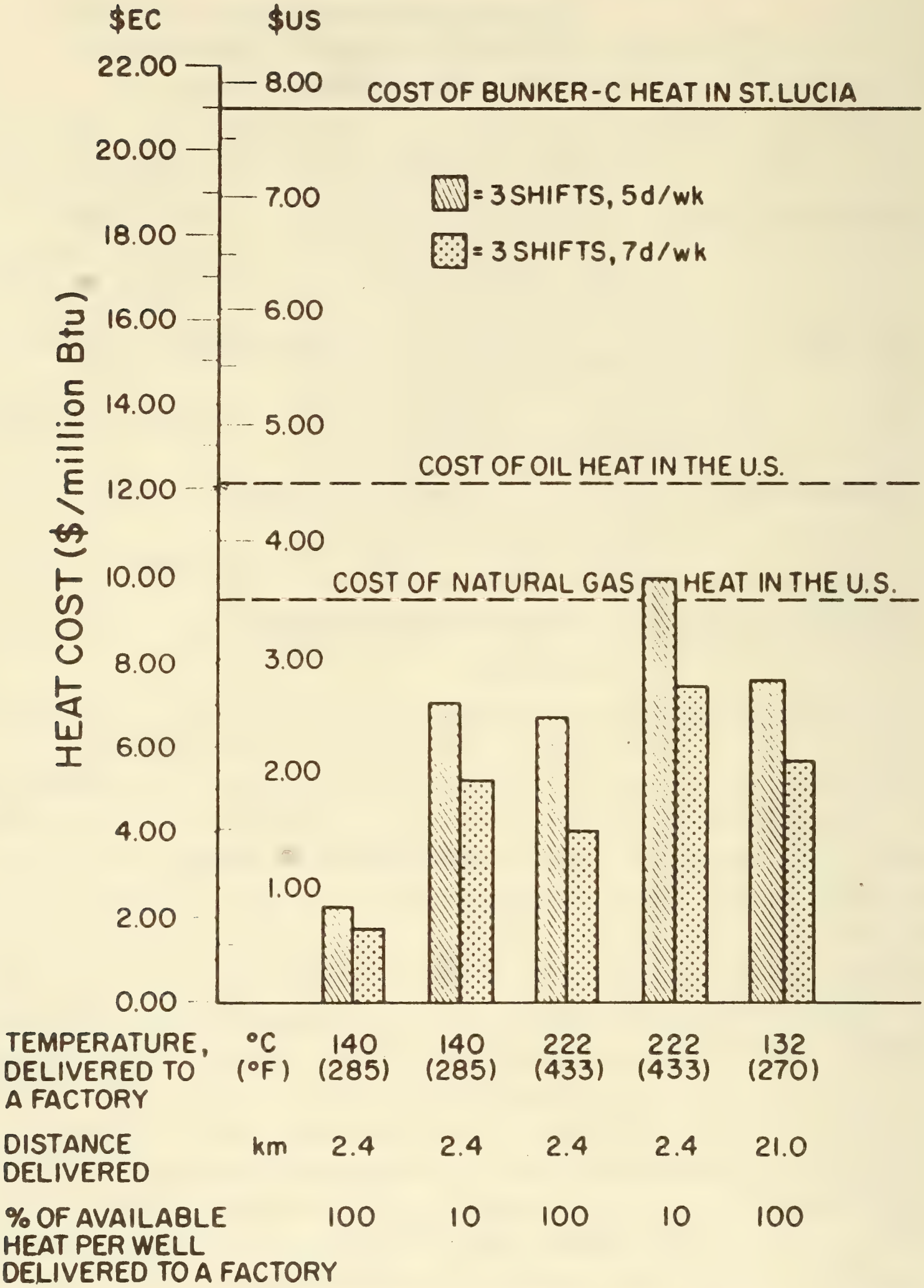

Fig. 8. Comparative costs of process heat (vertical bars represent costs for geothermal heat source).

Potential industries that could use process heat and are candidates for applying the St. Lucian geothermal energy to profitable operation would include: copra plants; timber processors; concrete-block factories; breweries; manufacturers of alcohol from sugar; manufacturers of dry ice; producers of banana

chips; tourist hotels; producers of potable water from steam; and alumina producers. Some of these industries are already represented on the island, while others might be attracted there by the availability of large supplies of cheap heat in a readily usable form.

Copra Plant

An existing copra processing plant in Soufriere produces 3300 gallons of coconut oil per day from 22 tons of coconuts. The plant employs about 100 people and consumes 135,000 Imperial gallons of Bunker-C fuel oil per yr. to provide approximately 3,000 pounds of steam per hr. at 142° C (288° F) for the refinery and 104° C (220° F) for the copra presses. The oil-fired boiler could be replaced by a heat exchanger connected to an insulated, 2-in. diameter, steel pipeline capable of pumping 30,000 pounds per hr. of hot water through a closed loop containing another heat exchanger at the well-head. The cost of the hot loop and heat exchangers could be prorated among other industrial customers in the Soufriere area for increased economy. This would, of course, require increasing the diameter of the insulated supply line to accommodate the flow requirements of the other plants.

Timber Processing

Over three quarters of the St. Lucian land-area is forested and produced the 113,730 board feet of lumber sold in 1982. Modern kilns for drying timber operate at temperatures between 38–93° C (100–200° F) and can dry approximately 15,000 board feet of lumber in a drying cycle, which varies from a few days to several weeks in length. A 2-in. insulated steel pipeline could deliver process heat from the geothermal plant to a timber drying kiln in the amounts required for continuous operation. A geothermally powered timber-processing industry in St. Lucia might also attract the import of raw hardwood from South and Central America, and the dressed lumber might be highly marketable for manufacture of furniture in the U.S. and Europe.

Concrete Block

Concrete block construction is used in most of the residential and commercial buildings built in St. Lucia and neighboring islands. St. Lucian construction consumes approximately 650,000 blocks per year. A modern, atmospheric pressure steam kiln for curing concrete blocks operates at 88° C (190° F) and requires an average of 1.2 million BTU per hr. An insulated, 2-in. diameter steel pipe heat-loop could deliver enough process heat from the geothermal field to a kiln suitable for meeting the concrete block requirements of St. Lucia and several of her neighbors.

Beer Production

A brewery in Vieux Fort, 21 km southeast of Soufriere, employs 109 people, produces approximately 6,000 bottles of beer per day and is sized for twice that rate. It currently consumes approximately 80,000 KWh of electricity and 5,000 Imperial gallons of Bunker-C fuel oil per month to generate steam at 150 psi and 161° C (322° F). An insulated pipeline from the geothermal field would cost an estimated $1.6 million (US), which might not be justified by savings in oil cost unless other industries in the Vieux Fort area shared the cost of the pipeline and the consequent savings from avoidance of conventional energy costs.

Alcohol from Sugar

By partially reviving its dormant sugar industry, St. Lucia could apply its geothermal energy to the production of enough industrial grade alcohol to replace approximately 500,000 gallons of motor fuel per yr. by adding alcohol to gasoline to form gasohol. Typical sugar cane yields for that region from 1500 acres in St. Lucia would be enough to feed a combined sugar-mill and distillery requiring about 4 million BTU per hr. at temperatures up to 218° C (425° F) to meet the gasohol production rate. An insulated, underground, 6 in.-diameter steel pipeline to deliver that amount of heat would cost approximately $30 (US) per ft., and an uninsulated return line installed in the same excavation would cost about $7.5 (US) per ft.

Dry Ice

The production of dry ice in St. Lucia could provide a readily transportable source of refrigeration for enlarging the fishing industry as well as for exporting dry ice to neighboring countries. Noncondensable gases contained in geothermal steam typically contain about 1% carbon dioxide, which would amount to approximately 1400 tons per yr. from each producing well. Dry ice production requires about 20,000 pounds of steam per ton of dry ice for driving compressors to increase the gas pressure to 1100 psi. The only other resource required is labor at the rate of 8 person-hr. per ton.

Banana Chips

The production and processing of 4.3 million banana stems per year is a major export industry in St. Lucia. The manufacture of banana chips from the estimated 10% waste from the harvesting and boxing operations might be an attractive new industry to capitalize on the availability of cheap process heat in St. Lucia. Deep frying the 10 million pounds of waste fruit per yr. to produce banana chips would require a plant costing about $750,000 (US) and consuming process heat at the rate of approximately 2 million BTU's per hr. Locating

such a plant at either Soufriere or Vieux Fort would allow it to share the costs and benefits of heat loops from the geothermal field to either the existing copra plant or the brewery now operating in those cities.

Tourist Hotel

A typical, 256-room tourist hotel in a tropical climate consumes 3.5 million KWh of electricity, 18.2 million gallons of water and 4.2 million standard cubic feet of natural gas for kitchen and laundry services per yr. The availability of competitively priced electricity and cheap process heat might induce existing hotels to convert to geothermal energy and attract new tourist hotels to St. Lucia.

Water from Geothermal Steam

The price of water treated adequately for human consumption and for industrial processes such as brewery operations in St. Lucia is approximately $2.25 (US) per thousand gallons, compared to less than $1 (US) per thousand gallons in the U.S. Geothermal energy in St. Lucia could be used as process heat in a multistage flash distillation system or as electricity to power a reverse osmosis system for converting seawater to potable water. However, neither of these approaches nor any other yet developed appears likely to be competitive in St. Lucia in the foreseeable future.

Another possible approach for producing fresh water could be to use condensate from the turbine exhaust and residual hot brine from the steam separator. This brine could be flashed again to separate a lower grade steam which could be condensed and combined with the condensed turbine exhaust to produce approximately 7,000 gallons of potable water per hr. from each 2.5 MWe unit. A 12-well geothermal complex using this approach could produce over 13 gallons per capita per day in St. Lucia for both domestic and industrial use.

Aluminum Production

Aluminum metal is produced from bauxite ore in two sequential, energy-intensive processes, with the intermediate production of white, powdered alumina. The conversion of two tons of bauxite to one ton of alumina requires steam containing 15 million BTU per hr. and 200 KWh of electricity. Preliminary estimates indicate that alumina might be produced in St. Lucia using geothermal energy for less than the current US market price. More detailed analysis after geothermal development has begun might prove the profitability of processing South American or Jamaican bauxite in St. Lucia to produce alumina as the feedstock for aluminum smelters. However, the production of aluminum metal in St. Lucia does not appear economically feasible in the foreseeable future, since large blocks of electricity (hundreds of megawatts)

would be required at 3 to 4 cents (US) per KWh in order to be competitive with large producers in the U.S.

Table 2 summarizes the energy requirements for several process heat applications described above. These five applications require a total of approximately 33 million BTU's per hr., or about one third of the assumed capacity of one producing well in the St. Lucia field. The production of alumina from imported bauxite ore has the potential for using all the heat delivery capacity from one such well. An energy intensive industry of this type could result in lower costs for all users serviced by the common system, since the smaller users would benefit from the economies of scale in transmission pipe diameters, pumping power, and delivered heat temperatures.

Economic Impact

Los Alamos developed an econometric model focused on the consumption and output components of the St. Lucian economy. The output equations dealt with the important private sectors of the economy, namely: agriculture, tourism, industry and services. The consumption equations considered food and beverages, fuel and light, and durable goods.

Exercise of this model resulted in forecasts of increased economic activity in these seven sectors over the next 30 yr. Figure 9 shows these results, measured as the predicted increase in consumption if St. Lucia converts from diesel to geothermal as the primary energy source. Two cases are shown: oil prices remaining constant throughout the period, and oil prices increasing at the rate of 2% per yr. through 2017. The constant oil price case shows an increase in total consumption of more than $20 million (US) in 1983 dollars during the 30-yr. period, and

Table 2.—Energy Requirements of Geothermal Process Heat Applications, St. Lucia

Location/Industry	Heat Req'd (Million BTU/hr)	Temperature (°C)	Flow (Lbs. of Steam/hr)
Soufriere			
Sugar-Alcohol Mill & Distillery	11.99	218 (max)	119,900
Copra Mfg. Ltd.	3.00	142 (max)	30,000
		71 (min)	
Timber Drying Kiln	0.40 (avg)	93 (max)	4,000 (avg)
Choiseul			
Concrete Block Manufacturing	13.30 (max)	88 (max)	133,000 (max)
	8.10 (avg)	88 (min)	81,000 (avg)
Vieux Fort			
Windward & Leeward Brewery	4.70*		47,000*
	1.05**	161 (max)	10,500**
Total	33.39 (max)	218 (max)	333,900 (max)

* Assumes 40-hr. work week.
** Assumes 168-hr. work week.

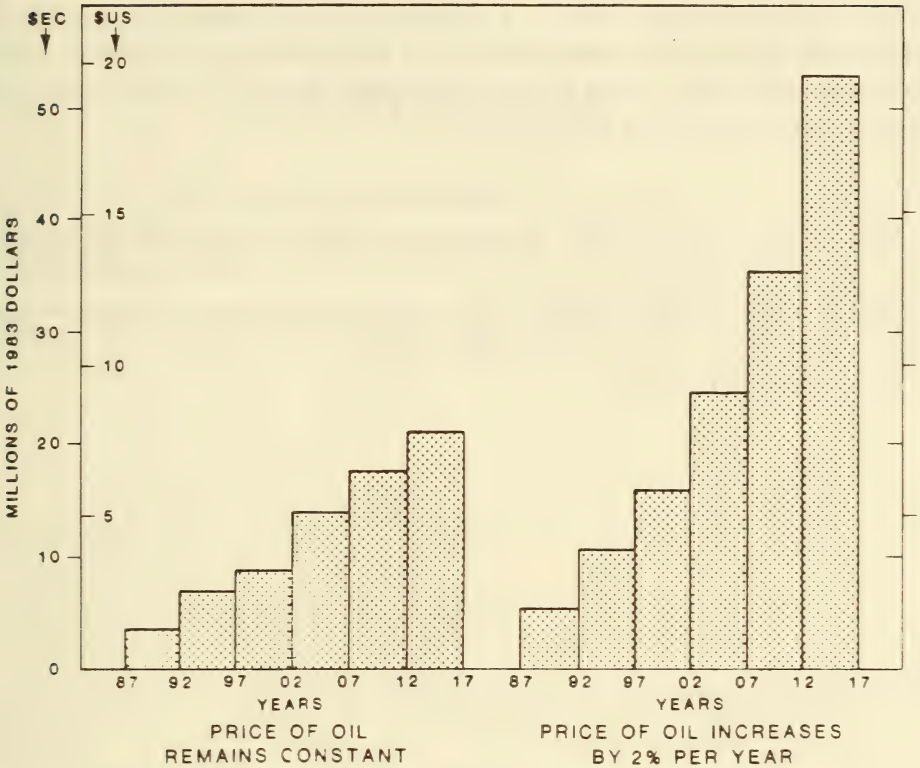

Fig. 9. Increase in annual consumption due to installation of geothermal power.

the 2% annual increase in oil prices more than doubles the projected increase in consumption.

Conclusions

Geotechnical, engineering, industrial and economic analyses (Altseimer et al., 1984; Hanold et al., 1984; Taylor, 1983) of all available data indicate that the geothermal resources underlying the island of St. Lucia can be developed by drilling production wells in the Qualibou Caldera near Soufriere and installing modular power generating units and process heat exchangers, insulated pipelines and power transmission grids to energy consumers. Based on very conservative estimates of construction and operating costs, the cost of geothermal electricity in St. Lucia should be more than 30% below current costs of diesel-generated electricity. The estimated costs of industrial process heat from the geothermal source range from 50% to 90% less than heat from Bunker-C fuel oil. Several existing St. Lucian industries and a number of new ones could benefit from the abundance of cheap energy which development of the geothermal

potential would provide. The St. Lucian economy is projected to grow at a significantly faster rate if geothermal energy becomes the prime source of electricity and industrial process heat on the island, even if the world price of oil remains constant over the next 30 yrs.

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Volume 81, Number 1, Page 43, March 1991

Corrigendum

Corrigendum should be noted within the article: Gluckman, A. G. (1990). The discovery of oscillatory current. *Journal of the Washington Academy of Sciences,* 80(1), 16–25.

(a) pg. 18, line 9 from bottom, change to . . . is the germinal *idea* in Savary's . . .

Notice

In issue number 4 of volume 80 (December, 1990), pg. 187, the corrigenda that were listed were not entirely correct:

(a) this item appeared on pg. 20 not on pg. 21.

(c) this item appeared on line 3 not on line 2; and in addition, the change should have included . . . "ADDITION au *Mémoire* de M[onsieur]. Savary sur l'Animantation".

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Perceptual Integration

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ABSTRACT

The concept of perceptual integration and evidence for that phenomenon is assessed with a review of representative experimental studies with complex activities in the areas of haptic, auditory, and visual performance by human observers. The phenomenon can be defined as a process of the sensory input systems that facilitates object recognition both within and across modalities. It is concluded that there are a sufficient number of positive behavioral findings in support of an integrative process, and experimental techniques are available that show promise for the direct observation of it mechanisms.

Introduction

The immediacy and ease of perception belies the complex analytic processing that operates on sensory information to enable human observers to achieve veridical knowledge about objects and events in the external world around them. Some theorists (Kubovy & Pomerantz, 1981) have adopted the view that the process is holistic, i.e., that the entire object is perceived first, and in later stages it is progressively analyzed into its constituent parts. This notion is sometimes called top-down to characterize a hierarchical analysis from the whole object that branches down to its particular parts. Yet the term top-down is used by other theorists to affirm that expectations about the object also guide an individual toward recognition of the object that could begin with either the whole object or its individual features. A different view, called ecological (Shaw & Bransford, 1977), states that the perceptual system detects higher-order, action-relevant properties of objects, such as their gradients and ratios, rather than their detailed features. There is also a considerable body of evidence (Treisman, 1986) that leads to the conclusion that perception arises through the decomposition of an object into its features followed by an information-processing stage that maps the physical representations into subjective experience. Fodor (1983) has posited the existence of input modules where complex objects are initially decomposed into their components by a set of independent, feature-analyzer systems. Perceptual experience occurs after the features are re-assembled.

In feature-recognition theory (Treisman, 1988; Treisman & Gelade, 1980) it is proposed that the partly independent modules extract, in parallel, the elementary features of an object. To illustrate that process, imagine the letter "T" printed on a card in red ink. There would be a "hue map" for color, a "shape map" for the horizontal line, and a "shape map" for the vertical line. When attention is focussed on the letter's location on the card, the information from the three "maps" becomes a composite representation of a red letter "T". Experiments on sorting time with those three features have demonstrated that each represents an independent dimension of the object.

The integration of features to form a percept have lead to studies that seek to understand the operative factors in that process within single and multiple sensory-systems and that objective is the primary concern of this review. Perceptual integration will be defined as a process of physiological input systems that facilitates detection, precedes and enhances recognition of objects, and operates both within and across sensory systems. The process is assumed to be the result of an amplification of sensory signals, the availability of additional and/or redundant information, and/or the combination of sensory signals that leads to the development of a new representation of the source object. Ryan's summary (1940) of the long history of research studies directed toward an understanding of the process of sensory facilitation, and the opposite effect of inhibition, provided sufficient evidence to encourage further investigations of those processes. Research on this topic is still at the stage of demonstrating the phenomenon rather than pursuing systematic studies to define its important parameters, to describe lawful effects of experimental conditions, and to provide theoretical constructs for a general understanding of the process.

If these latter stages of research progress are successfully completed, the process might be useful for the development of techniques to achieve more effective and efficient human performance in a variety of settings which require the detection and recognition of target signals of low amplitude, when there is minimal attention on the part of the observer. One task domain where the effective combination of sensory signals became a practical question was sonar watchstanding. It was asked whether the success of a sonar operator who listens for faint, acoustic signals of a target, could be improved if, at the same time, an image of the same target was displayed visually. In one example of studies that were directed at conditions that might lead to the enhancement of the sonar-operator task, O'Hare (1956) found significant shifts in acuity for pure tones (up to 3.9 db) during concurrent exposure to a visual image that was varied in color, as tested by standard procedures. No simple statement could describe the effects observed. A yellow color patch (300 cd/m^2) always induced an increase in auditory sensitivity if any shift occurred but that effect could have been related to the

greater brightness of the yellow patch. However, that possibility did not fully account for the data because the yellow patch exerted less and less effect from the low to high tones. It was concluded that the feature of color can be of importance in intersensory effects on auditory detection thresholds.

Integration of Complex Signals

Though the phenomenon of audio-visual interaction has been established, its practical importance is diminished when it is realized that an increment in auditory acuity of 3 db could result from sending the same auditory signal to both ears instead of one (Pollack, 1948). Nonetheless, despite the prospect of meager practical gains based on studies of concurrent stimulation, using highly controlled stimuli, there has been a continued interest in the process as potentially useful with more complex, naturally occurring stimuli. A group of experts on the Naval Studies Board (1988) has recommended that research resources be committed to that topic. In addition, a recent research study (Doll & Hanna, 1989) has provided positive evidence of audio-visual interactions, and it is indicated that research interest is motivated by a search for operational techniques to enhance detection in the sonar watchstanding task, as underwater sounds from machinery noise emitted by other platforms and from other sources are more effectively attentuated.

Another impetus for looking again at the process of integration is the willingness of investigators to examine complex events rather than to confine their attention to the perception of highly controlled, unidimensional sensory events. The term complexity refers to many characteristics of information, such as numerosity, density, number of control paths and linkages, and levels of abstraction. With visual figures, complexity is stated as increasing with the number of edges, corners, contours, and turns (Chipman, 1977). This review examines representative behavioral studies that have provided positive evidence of integrative processes in order to assess the promise of further research effort on those phenomena. Studies that have used complex activities have been reported in the domains of haptics, audition, and vision, and they will be the focus of this analysis.

Haptics

Haptic systems incorporate information from sensors in the skin, muscles, tendons, and joints, to achieve purposive touch. The evidence for haptic integration is focussed on cross-modality effects between the cutaneous and motor systems when an individual grasps an object. Studies have examined how the

Table 1.—Haptic Procedures that are Associated with Acquiring Knowledge of Objects (Lederman & Klatzky, 1987)

Object Dimensions	Explanatory Procedures
1. Substance	
texture	lateral motion (LM)
hardness	pressure (PR)
temperature	static control (SC)
weight	unsupported holding (UH)
2. Structure	
weight	unsupported holding (UH)
volume	enclosure (EN); contour following (CF)
global shape	enclosure (EN)
exact shape	contour following (CF)
3. Function	
part motion	part motion test (PMT)
specific function	function test (FT)

dimensions of an object are combined and what happens when one of those dimensions is withdrawn. Those outcomes have been confirmed by observations of the exploratory procedures employed by the same participants during object recognition. The theoretical explanation for the occurrence of integration rests on the notion of motor and/or regional compatibility of the two sensory systems.

There are stereotypical hand movements, i.e., exploratory procedures, which are associated with the recognition of an object's dimensions. Those dimensions have been grouped (Lederman & Klatzky, 1987) into the three classes of information that blind-folded observers utilized to recognize an object: substance, structure, and function (Table 1). Lederman and Klatzky asked their observers to explore the objects freely and to match them to a standard object; the observed motor patterns were consistent for each dimension. In the process of making those observations, the investigators noted that some of the exploratory procedures led to above-chance performance for more than one object dimension. This finding led to the subjective impression that the object dimensions formed a coherent whole and suggested to Lederman and Klatzky that an integrative mechanism for haptics was at work.

The integration of three object dimensions is seen in Figure 1 (Klatzky, Lederman, & Reed, 1989). Response time, on the ordinate, is the interval (in ms) between touching an object and the verbalization of a correct recognition of a standard object. The observers used the dimensions of shape (S), hardness (H), and texture (T), to classify the objects. The use of those dimensions is inferred by the experimenter from the exploratory procedure(s) employed by the observers. It is evident that a given procedure can be used to perceive more than one dimension (Table 1) and exercising a given procedure allows the observer to

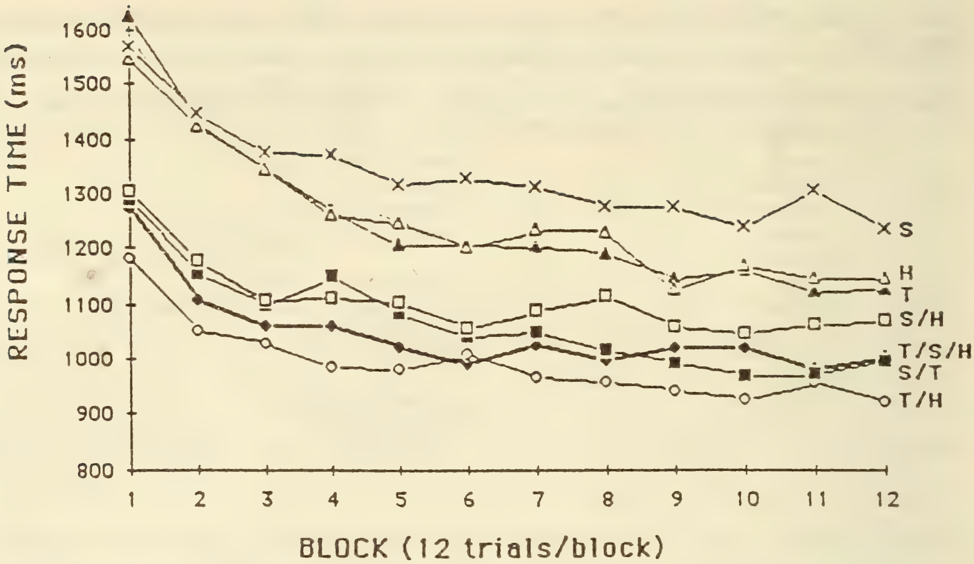

Fig. 1. Speed (msec) in the identification of objects of one, two, and three dimensions, over a series of trials (Klatzky, Lederman, & Reed, 1989).

sense other dimensions of the object, so that the research studies have been designed to minimize those confounding factors. Smooth curves can be drawn through the mean data points (12 blocks of 12 trials each) for the three curves that represent single dimensions. Such curves would depict the expected effects of practice and the attainment of asymptotic performance. Where pairs of dimensions (S/H, S/T, T/H) were used by the observers, response times were significantly lower and also reached asymptotic levels. However, there were no additional gains when three dimensions (represented by T/S/H) were employed by these observers.

These investigators devised another experiment on the observer's use of paired dimensions to recognize an object. After the observers had reached an asymptotic level of performance, one of the dimensions was made constant, or effectively, withdrawn (W/D). If performance remained unchanged, it could be inferred that the observer had not really been using the constant dimension, i.e., no integration had occurred.

The clearest results are shown in Figure 2 where texture and hardness were the paired dimensions (Klatzky, Lederman, & Reed, 1989). In the upper curve, removal of the texture dimension led to an immediate increase in response time which did not return to its former asymptotic level in subsequent trials. The same results occurred, but with greater effect, in the lower curve, when hardness was withdrawn as an object dimension. This is clear evidence for the presence of integrative action.

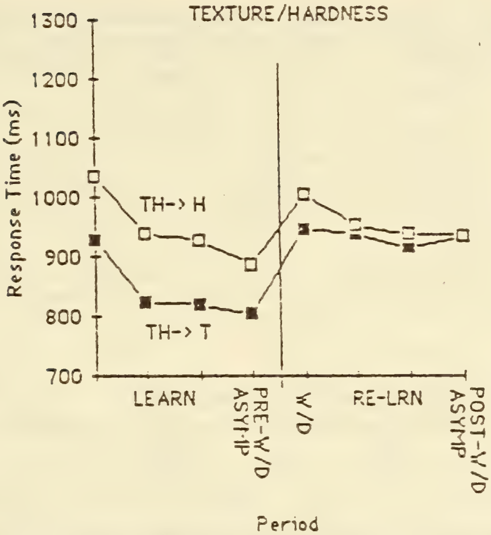

Fig. 2. Speed (msec) in the identification of objects that vary in the dimensions of texture and hardness, and after one of those dimensions remains constant (Klatzky, Lederman, & Reed, 1989).

Another view of the respective roles of these two object-dimensions can be seen during an examination of the exploratory movements of the same observers. Recall that for the recognition of texture, the initial studies (Table 1) showed that lateral movement (LM) was the exploratory procedure used; and for the recognition of hardness, pressure (PR) was identified as the procedure that would be employed. The procedures of enclosure (EN) and contour following (CF) were observed when shape recognition was required.

Figure 3 depicts the results of a study in which the texture and hardness dimensions were paired (Klatzky, Lederman, & Reed, 1989) and the observers reached asymptotic performance in the recognition of the objects (designated as pre W/D). It can be seen that lateral movement (LM) and pressure (PR) were used about equally in those judgments. At a later interval (designated EXPL), new objects were introduced and freely explored by the blind-folded observers. Enclosure (EN) and contour following (CF) movements were elicited but LM and PR movements predominated. In the third interval (labelled TEST), object hardness was made a constant dimension and PR movements dropped sharply but LM activity rose. At the last interval, asymptotic performance was reached. These curves reflect the separation of the integrated movements when one of them no longer remains as an effective basis for the observer's judgments.

The same experimental design is shown in Figure 4 where texture became the constant dimension (at TEST) and the frequency of LM movements plummeted (Klatzky, Lederman, & Reed, 1989). The same inference can be made that a previously integrated movement had become separated.

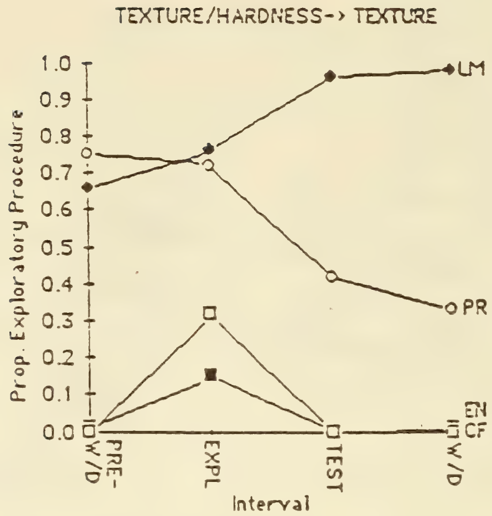

Fig. 3. Proportion of four exploratory procedures that are utilized in the identification of objects that vary in the dimensions of texture and hardness, and after the hardness dimension remains constant (Klatzky, Lederman, & Reed, 1989).

These investigators discovered in subsequent studies that the use of the extra dimension was spontaneous even when the observers were instructed to attend to only one object dimension.

The strongest experimental evidence was for a linkage of the exploratory

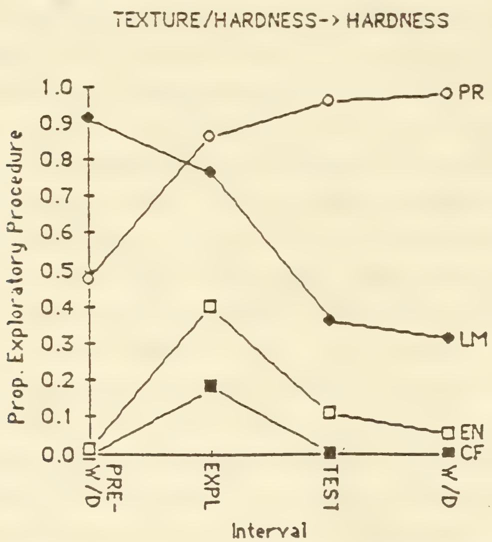

Fig. 4. Proportion of four exploratory procedures that are utilized in the identification of objects that vary in the dimensions of texture and hardness, and after the texture dimension remains constant (Klatzky, Lederman, & Reed, 1989).

Table 2.—Mean Pointing Error (Degrees and Percent) During Auditory and Visual Localization as a Function of Angular Separation of the Target and Competing Signal (Bertelson & Radeau, 1981)

	Mean Pointing Error			
	Visual Bias		Auditory Bias	
Separation (Degrees)	Degrees	Percent	Degrees	Percent
7	3.99	57.0	.34	4.8
15	6.27	41.8	.47	3.1
25	8.16	32.6	.61	2.4

procedures associated with texture and hardness. The explanation for the results was that there was a motoric compatibility, i.e., the motor pattern incorporated both exploratory procedures. Other exploratory procedures which led to significant integrative results were explained as regional compatibility, i.e., the motor patterns focused on the center, thickness, or edges of the object.

Audition

The auditory system processes speech and non-speech acoustic signals but there is evidence that motor components are integrated into the perception of both types of signals. Three areas where evidence of perceptual integration have been pursued include: (a) auditory and visual interaction; (b) phonetic and visual location; and (c) compression of acoustic features into a single image. They will be examined in turn.

Interaction. One approach that has been employed in the study of intersensory interaction has been to ascertain whether visual stimulation biases an observer's response to an auditory signal, and vice versa. In Table 2 are shown some experimental data on pointing errors as angular separation between a target signal and a competing signal in a different sensory modality was varied randomly (Bertelson & Radeau, 1981). When the target signal was visual, a visual-bias condition is created because the observer was instructed to attend to that target; and when the target was changed to an auditory signal, an auditory bias was obtained, in the same manner. Results indicated that when the angular separation between the target and the competing signal was increased, absolute pointing errors increased significantly for both auditory and visual conditions. However, pointing errors were much larger (8 degrees) when the target signal was visual than when the target signal was auditory (less than 1 degree).

A second study examined whether the bias from a competing signal depended on the signal's perceived source. In that experiment, observers not only pointed at the source of the target signal but also indicated whether the competing signal came from the same source.

Table 3.—Mean Pointing Error (Degrees and Percent) During Auditory and Visual Localization as a Function of Angular Separation of the Target and Competing Signal, and Accuracy of Source Identification (Percent Same) for the Target Signal (Bertelson & Radeau, 1981)

	Mean Accuracy of Source Identification and Mean Pointing Error		
Separation (Degrees)	Source Identification (Percent Same)	Degrees	Percent
		Visual Bias	
7	79	3.39	48.4
15	48	4.36	29.1
25	12	3.88	15.5
		Auditory Bias	
7	74	.19	2.7
15	38	.31	2.1
25	21	.13	.5

In the visual mode (Table 3) the observers showed a significant error for all three separation levels. Although the absolute-error in degrees was similar across the three separation-levels, the percent bias decreased with increasing separation. In the auditory mode, non-significant levels of absolute error were obtained. The percentage of trials on which the observers reported that the target and competing signals were from the same source declined with increases in angular separation.

When the data attributed to the same source are calculated separately from the data where the observers said that the signals were from a different source, pointing errors did not increase with separation on "different" trials but increased markedly on "same" trials. This outcome was interpreted to mean that in the decision process, there is not just a visual modality bias but that there is a shift in the location of the criterion for perceptual fusion based on the spatial data from a competing auditory signal.

Phonetic location. A vivid result has been reported on the integration of phonetic and visual location by McGurk & MacDonald (1976) when speech and visual information were placed in conflict. A video recording showed a talker producing a consonant-vowel syllable while a dubbed sound track produced a different consonant-vowel syllable. Thus, when the sound of "ba-ba" was mixed with a video recording of "ga-ga", 98% of the adult listeners reported a fused sound, "da-da". If they closed their eyes, the sound reverted to "ba-ba". These authors do not provide a strong explanation for these results but Summerfield (1979) suggested that the dimensions may be amodal, i.e., the neural code for the visual and auditory properties may have the same representation in both modalities.

An alternative explanation to that provided by Summerfield can be derived

from modularity theory (Fodor, 1983) which argues that for perception there are independent input systems or modules with distinct properties. One of those properties is that the analyzers within the input systems have shallow outputs, i.e., they tend to solve the tasks they were designed to solve. The modules of the auditory system have been divided (Liberman & Mattingly, 1989) into two classes: open and closed. Open modules are for pitch, loudness, and timbre; they are adapted for the perception of a large number of acoustic events. Closed modules provide specialization and require synthesis for the formation of their more complex outputs, e.g., phonetic perception or echo-ranging. It is likely that integrative effects would be seen more readily among functions mediated by closed systems. Summerfield conjectured that simple energy properties were interacting at a level equivalent to open modules; however, the magnitude of effect at that level would be small, i.e., in the case of audition, no greater than a few decibels. The concept of closed modules is more suitable for an understanding of the occurrence of the qualitative changes reported by McGurk and MacDonald.

Acoustic images. Echo-ranging data have provided another source of evidence on integration. Recent research findings (Simmons, Moss, & Ferragamo, in press) on echo-ranging in the brown bat have revealed some of the processes that are employed by that organism in capturing, with the aid of acoustic images, a food object rather than an inedible sphere of the same size. The echo-locating bat integrates information on the absolute distance of the target and its shape into an unified image of the food object.

Brown bats perceive images of targets that explicitly represent the location and spacing of discrete glints from those targets, using echo delay and echo spectral representations that taken together resemble a spectrogram of the echoes (Figure 5). Two glints, A and B, from the moth reflect the acoustic emissions from the bat and the resultant range distance. They are received by the bat as two echoes. Echo A at time "t", and echo B at time "t + delta t". The bat's auditory system encodes these echoes so that time, frequency, and amplitude dimensions of the spectrogram are compressed into an image that has only time and amplitude dimensions (Figure 6).

The spectrogram-delays at each frequency are represented as a target-range map in the auditory cortex of the bat for glint A and at a slightly later time for glint B. Through this transformation, the bat synthesizes a perceptual dimension of "target range" that is an integration of absolute distance and the shape of the target.

Visual Recognition

A few classical experiments will be considered to provide evidence of integrative action in the visual system. The integration of visual dimensions has been

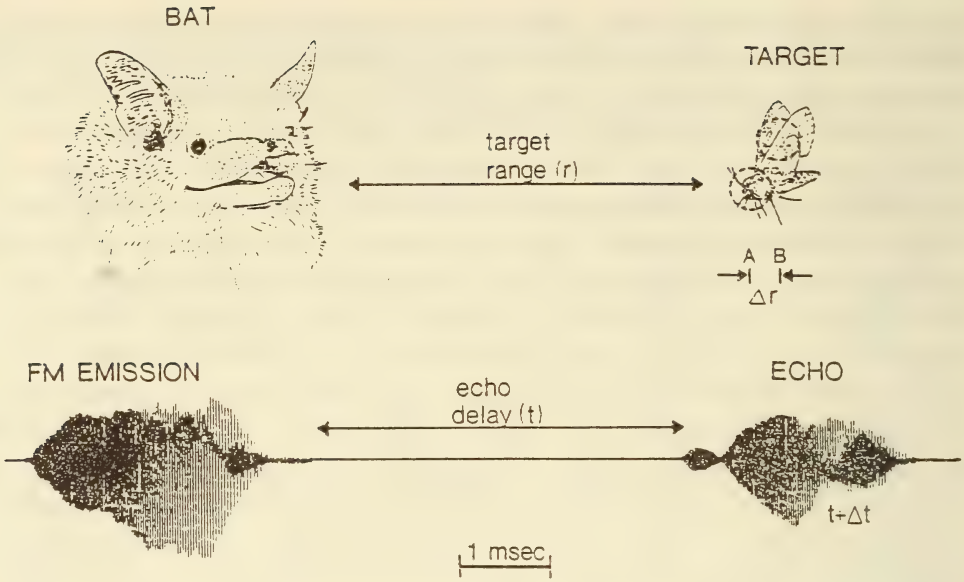

Fig. 5. Acoustic events with frequency-modulated (FM) emissions during the detection and recognition of prey by the brown bat (Simmons, Moss, & Ferragamo, in press).

the object of study by a large number of investigators (Garner, 1970, 1974; Treisman, 1986, 1988) and has led to the definition of those dimensions as either integral or separable. A dimension is separable when the level along one dimension can be expressed without requiring the specification of the level of the other. Integral dimensions, on the other hand, are dependent or correlated with each other.

Speed in sorting or classifying objects (Garner & Felfoldy, 1970) has been employed to demonstrate the existence of integrality. An example is seen in Table 4 where the results of an experiment in which colored chips, which varied along the dimensions of brightness and hue, were sorted into two categories.

Mean sorting times (s) are shown in the first column when only one dimension was used as the basis for placement into one of two classes of brightness or hue. The second column shows the outcomes when the observers were instructed to sort by one dimension but were not informed that the other dimension was correlated with that dimension, i.e., it was redundant. The observers could have sorted correctly by either dimension. There is a significant reduction in sorting time for both dimensions. This facilitation of sorting time is a property of integral dimensions. Finally, the observers were instructed to sort on one of the dimensions but were not informed that the other dimension would be changing, in an uncorrelated or orthogonal fashion, with that dimension. The result was a significant increase in mean sorting time. This interference with sorting

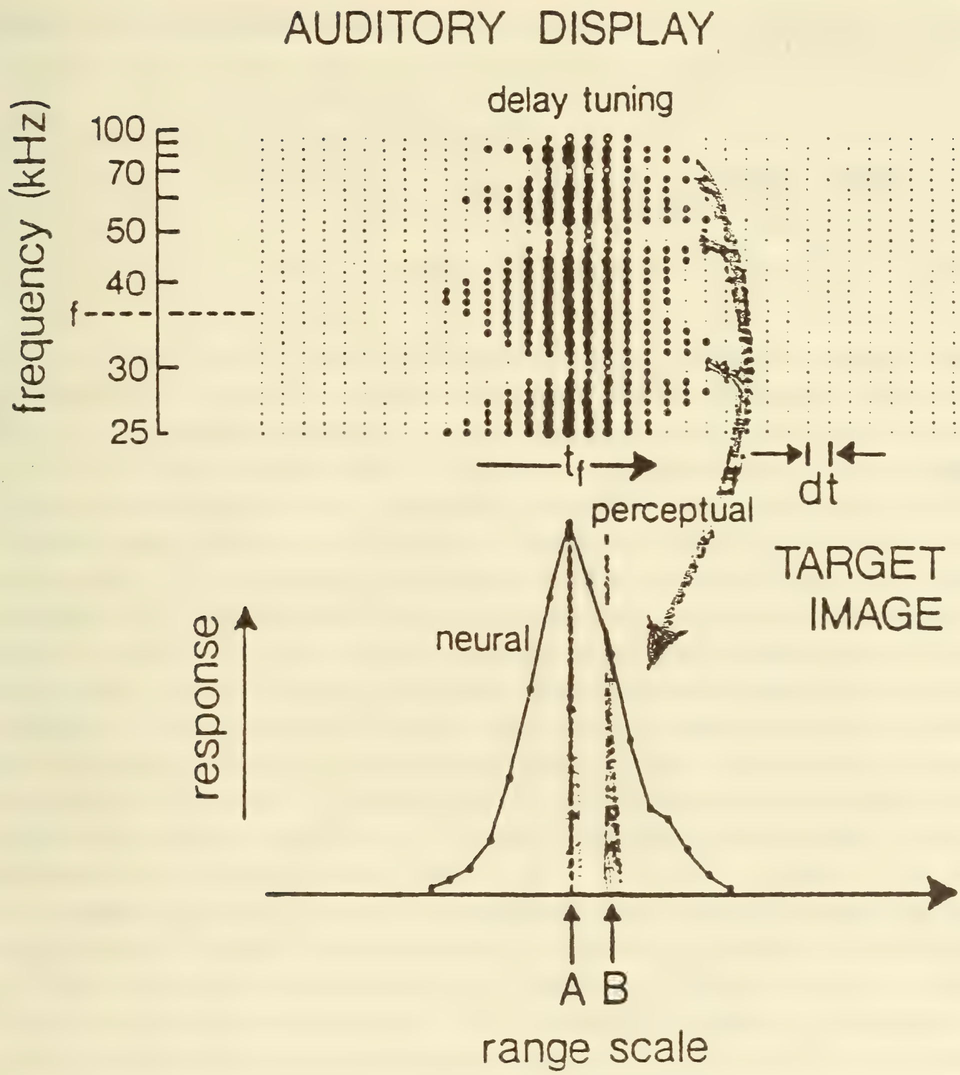

Fig. 6. Formation of an image of "target range" by the brown bat from echoes of target distance and shape elicited from prey (Simmons, Moss, & Ferragamo, in press).

time is a property of integral dimensions under these conditions, and provides converging evidence for the definition of integrality.

Another example of this same pattern of effects is shown in Table 5. Mean sorting times (s) have been obtained from observers on the basis of the horizontal or vertical position of a single dot. The next column shows the results when the observers were instructed to sort by one dimension but were not informed that the other dimension was correlated with that dimension (Garner & Felfoldy, 1970). There was a significant reduction in sorting time for both dimen-

Table 4.—Mean Sorting Time (sec) for Objects that Vary in Brightness and Hue, and Type of Relationship (Garner & Felfoldy, 1970)

	Mean Sorting Time (sec) Character of Dimensions on Visual Image		
Dimension to be Sorted	One	Correlated	Orthogonal
1. Brightness	15.09	13.73	18.55
2. Hue	14.22	13.24	17.49

sions which is a sign that the dimensions are integral. When the observers were instructed to sort on one dimension while the other dimension was changed randomly, the result was a significant increase in mean sorting time. Both facilitation and interference effects are consistent with integral dimensions.

There are other studies on gains in performance when redundant information is added to a visual image and further evidence for the existence of the integration of information. Some cautions have been raised on the need to control for limitations in the process, i.e., that the dimension being sorted is discriminable to an ordinary observer. And in addition, controls need to be made in those experiments for state limitations, e.g., that the conditions when the dimension is being sorted are of sufficient contrast to be seen, or not of such a short duration that they are missed. The foregoing findings have supported the notion that integrality is a property of the physical characteristics of an object but there are other studies (Pachella, Somers, & Hardzinski, 1981) that indicate that integrality is, in addition, a property of the psychological processes of the observer. Pachella et al. established that additional fact by using the statistical method of multidimensional scaling to map the physical specifications of a set of signals into a set of psychological attributes. As judged by human observers, when the correspondence between the specifications and attributes was high, those dimensions had the property of integrality; however, when that match was low, they did not.

Table 5.—Mean Sorting Time (sec) for Dots That Vary in Horizontal and Vertical Position, and Type of Relationship (Garner & Felfoldy, 1970)

	Mean Sorting Time (sec) Character of Dimensions on Visual Image		
Dimension to be Sorted	One	Correlated	Orthogonal
1. Horizontal	18.30	16.91	19.36
2. Vertical	17.51	16.24	17.95

A Direct Methodological Approach

The evidence for perceptual integration has been based on behavioral data and the concept would be more persuasive if concurrent, direct observation of brain functioning congruent with those other findings could be obtained. One approach that shows considerable promise toward that goal is the technique of positron emission tomography scanning which measures activity-related changes in regional cerebral blood-flow that identifies brain areas that are more highly active during a mental task (Marshall, 1988). A radioactive isotope that can attach itself to red blood cells is introduced into one of the main arteries that supply the brain. A gamma-camera monitors the radioactivity counts from the different brain regions and those counts are transformed into measures of regional cerebral blood-flow that reflect the differential activity of brain areas when a patient or volunteer is engaged in a mental task. The data from the camera are processed in a computer and images are displayed on a color monitor in which different hues are assigned to different levels of blood-flow. The radiation dose is low, the half-life of the isotope (e.g., oxygen-15) is brief (123s), and the data acquisition interval (40s) fast enough so that repeated measurements on diverse tasks can be obtained from the same person. The spatial resolution of the adjacent point sources is poor (about 1 cm) but a single source can be localized fairly accurately (about 5 mm). Image-analytic strategies, that lead to increased cerebral blood-flow as in a task that is intense and focal, can generate functional zones separated by less than 3 mm (Fox, Mintun, Raichle, Miezin, Allman, & Van Essen, 1986).

For those tomographic studies, a "subtraction" methodology has been devised to isolate component mental operations (Petersen, Fox, Posner, Mintun, & Raichle, 1988; Posner, Petersen, Fox, & Raichle, 1988) in a stimulus-target state that was not present in a control or resting state. Each new behavioral task adds a further processing requirement to the prior one, and blood-flow measurements from the simpler task are subtracted to obtain an image of the successive stages of the more complex tasks. This experimental technique showed that there were distinct cortical areas for: (a) passive processing of visual forms; (b) generation of a use for a word after it is heard; and (c) monitoring the frequency of occurrence for a target type. Results indicated that the locations of the separate brain areas involved in the visual and auditory coding of words, each with independent access to supramodal articulatory and semantic systems. These findings fit in well with parallel models of perception. Other studies with this technique (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990) have demonstrated sensitivity to the visual attributes of shape, color, and velocity of visual

stimuli. This technology represents an effective means for a fresh approach to the investigation of integrative mechanisms.

Summary

The foregoing review supports these conclusions:

(a) Positive evidence is available of integrative processes in haptic recognition, across sensory and motor processes. The processes led to a significant enhancement of performance with two dimensions but no additional improvement occurred when three dimensions were made available.
(b) In the auditory domain, integration has been shown to occur with the visual modality for the localization of sound.
(c) In the speech domain, integration has been shown to occur across the visual modality for the recognition of a phonetic sound.
(d) In the echo-locating brown bat, the spectral and temporal features of an echo have been shown to be compressed into a single integrated quantity for the recognition of its prey.
(e) In the visual domain, studies of multi-dimensional signals have developed techniques for identifying integral and separable dimensions of a visual image.
(f) Positron emission tomography scanning has emerged as a feasible technique for the isolation and identification of potential mechanisms that participate in integrative processes.

These results have demonstrated that there are sufficient bases for systematic studies of perceptual integration across the modalities of haptics, audition, and vision, in which the focus would be on exploring processes at several stages of perception:

(a) interaction across modalities;
(b) interaction of signal parameters within a given modality that leads to the formation of a new representation; and
(c) interaction of signal parameters within a given modality that provides redundant information about that signal.

There is sufficient theory to guide research toward a plausible explanation of how sensory input systems mediate signals and the conditions under which those systems could interact with each other. Systematic studies of these findings could have a practical value for an improved understanding of the role of redundant, irrelevant, and compressed dimensions in the formatting of information. Moreover, general principles of integration could be useful for developing procedures for data fusion that would reduce complexity in information-processing tasks.

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The Gap Between Experimental And Psychometric Orientations

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ABSTRACT

With the increasing specialization of psychological research, there is danger that investigators may lose contact with other relevant specialties, as illustrated by the widening gap between experimental and psychometric orientations. Because variability—both within and between individuals—is an essential feature of human behavior, the experimental psychologist needs to include a statistical approach in both experimental design and data analysis. Notable examples of the merging of statistical and experimental methodology include analysis of variance, structural equation modeling, and factor analysis. A brief overview of the development and current status of these three procedures is provided.

One of the inevitable consequences of the rapid growth of psychology is an increasing specialization in the training and functioning of psychologists. Specialization is obviously needed if one is to attain sufficient depth of knowledge and expertise to make an effective contribution to either research or practice. At the same time, specialization creates hazards which are becoming increasingly apparent in psychology. There is the likelihood of losing contact with neighboring specialties that may be relevant to one's work. And there is the danger that the methodological focus becomes too circumscribed to provide an adequate picture of so complex a phenomenon as human behavior. As a result, one's data may be incomplete and one's conclusions incorrect.

This weakening of contact is what I see in the widening gap between the psychometric and the experimental orientations in psychological research. As long ago as 1966, in my address to APA Division 5 (Division of Evaluation and Measurement), my main thesis was that psychological testing was becoming dissociated from the mainstream of contemporary psychology (Anastasi, 1967). Psychologists specializing in psychometrics had been concentrating more and more on elaborating and refining the techniques of test construction, while losing sight of the behavior they set out to measure. As a result, outdated interpretations of test performance remained insulated from the impact of the grow-

ing knowledge base provided by behavioral research. I argued then—and I have continued to argue—that much of the criticism of testing stems from the isolation of psychometrics from other relevant areas of psychology. Because I am now talking to members of Division 21 and the Human Factors Society, I shall look at the other side and try to see what the gap may mean for experimental psychology.

The Psychometric Orientation

First, what do I mean by the psychometric orientation? I define the field of psychometrics methodologically, to include psychological testing and statistical analysis, and substantively, as covering the nature and sources of individual differences (i.e., differential psychology). The psychometric orientation is essentially statistical, because it takes variability as a basic phenomenon to be investigated in its own right. Statistical methodology was originally developed as a means of dealing with variability. It is needed in analyzing any data on human behavior, because human behavior presents extensive variability in many forms.

Not only is there wide variability in the responses of different individuals, but there is also variability among specific response indicators, such as the items making up a test. The latter kind of variability is typically assessed by measures of a test's internal consistency, as with the Kuder-Richardson reliability or various split-half reliability coefficients. There are also random differences in response over time, which reflect the many variables that may affect an individual's performance over short time intervals, including both changes in the individual's physical and psychological condition and changes in the external situation. The usual retest reliability refers to this kind of random variability. These random changes should be distinguished from systematic, progressive and cumulative changes, such as would result from learning and other lasting changes in the person.

It is noteworthy that in the early days of experimental psychology all forms of random variability were regarded as "errors" insofar as they tended to restrict the applicability of general findings about human behavior—which was what most nineteenth century psychologists were looking for. Hence we have inherited the error nomenclature, in standard error, error variance, and so forth. To the psychometrician, however, these are not errors that could be prevented by improved procedures. They are inalienable facts of behavior to be taken into account.

Variability will not go away if you ignore it. If ignored, it remains to distort

your results and probably lead to a wrong conclusion. The psychometric orientation concerns not only the sorts of variability assessed by sampling errors and errors of measurement, which can be handled by checking the statistical significance of mean differences, finding the confidence interval of a score, or looking up the significance of a correlation coefficient. It concerns also the variability among persons, as represented by the total distribution of performance measures. Thus it is not only the standard error of a mean that we are concerned with, but the standard deviation of the whole distribution. We may want to know what range of individual variation would be appropriate to consider for a particular purpose. Should it be 1.96 times the standard deviation on both sides of the mean, which would cover approximately the middle 95% of the group? Or should it be a narrower or a wider range? Such questions deal with real, objectively assessed individual differences in performance. They are as close as you can get to empirically observed facts.

Another example is provided by the correlation coefficient, which we all take for granted. The reason we need correlation coefficients is because the relation between any two variables varies from person to person. If the same relation between two variables held for all persons, such that each person occupied the same relative position in both variables, the correlation between the two variables would be +1.00 and we would not need to compute it. But in reality, one individual may be high in both variables, another high in one and mediocre in the other, still another above average in one and below average in the other, and so on. The size of the correlation coefficient tells us how much individuals differ in the way the two variables are related. Had we administered a whole battery of tests, a score profile for each person would reflect this kind of individual difference. Such score profiles could prove especially useful in assigning persons to different training programs, different jobs, or different experimental treatments of any sort.

Some Notable Mergers of Statistical and Experimental Methodology

Intrinsically, there is nothing in either statistical or experimental procedures that keeps them apart. They are two highly compatible aspects of scientific method. In this connection, there is a favorite story, which is not apocryphal; it tells of an experience that has probably occurred many times to young researchers in psychology. The investigator in the story has been busy collecting an extensive body of data in the effort to test one or more hypotheses. Faced with an overabundance of numerical data, the investigator decides to consult a well-known statistician for expert advice on how to analyze the data. The statistician

tries to do the best that he or she can to help, but with a sad shake of the head, remarks, "I could have been of real help if you had contacted me *before* you gathered your data." This, of course, is the question of experimental design, which is closely linked to statistical considerations.

Analysis of Variance

A clear example of this linkage is analysis of variance, familiarly known as ANOVA. R. A. Fisher (1925), who introduced ANOVA in the 1920's, was Chief Statistician at the Rothamsted Experimental Station, a British agricultural research center. In Fisher's own writing and lecturing, considerations of experimental design constituted a major portion of his treatment of ANOVA. When ANOVA was subsequently adopted by psychological researchers, it was used chiefly to assign individuals to groups in order to identify the effect of specific experimental variables. The simplest application involves the comparison of control and experimental groups, in order to assess the effect of the experimental variable on performance. A major contribution of ANOVA, however, was to permit the simultaneous study of the effects of several independent variables, including both experimentally manipulated and naturally occurring variables. For instance, we could assess the effect of sex and socioeconomic level on mechanical aptitude test scores. With two independent variables, we can measure not only the total effect of each variable, but also the interaction between the two. Thus the results might show that in high socioeconomic levels there was no significant sex difference in mechanical aptitude, while in low socioeconomic levels the men performed significantly better than the women.

To take an example with experimentally manipulated variables, suppose we wish to evaluate two training methods for instructing trainees in the performance of an occupational test. On the basis of scores on a general aptitude test,[1] we divide the trainees into three groups (high, medium, and low), with 40 persons in each group. Of the 40 high-aptitude persons in Group 1, 20 are taught by Method A and 20 by Method B. The 40 in the middle-scoring group are similarly assigned to the two methods, and the same assignment is followed for the low-aptitude group. If we compare overall mean task performance of the three groups after training, we would probably find that the high-aptitude group performs best and the low-aptitude group poorest. But when we compare the two training programs *within each aptitude group,* we may find that Method B is more effective than Method A for the high-aptitude trainees, while the reverse is true for the two lower-aptitude groups. This would represent a significant inter-

[1] Such as the College Board's Scholastic Aptitude Test (SAT) or the AFQT composite of the Armed Services Vocational Aptitude Battery (ASVAB).

action between training method and aptitude level, a finding for which there is considerable empirical evidence (see, e.g., Berliner & Cahen, 1973; Bialek, Taylor, & Hauke, 1973; Cooper, 1974; Cronbach, 1975; Cronbach & Snow, 1977; Fox, Taylor, & Caylor, 1969).

As we add more independent variables to our experimental design, we can compute three-way, four-way and progressively higher-order interactions; but as the number of variables within a single study increases, we need very large samples in order to demonstrate statistically significant interactions. For practical purposes, available basic research on the interaction of specific variables can suggest guidelines in the construction of two or three trial programs, which can then be empirically tested as whole programs with groups that differ conspicuously in personal characteristics (Bialek, Taylor, & Hauke, 1973).

The concept of interaction among variables provides the theoretical rationale for tradeoffs in optimizing personnel procedures. Job performance is being viewed increasingly within a comprehensive system that integrates the effects of personnel selection and classification, training procedures, and job variables upon individual performance. Such a system covers multiple aptitude and personality variables of the worker, features of the training program, nature of job activities, equipment design, physical characteristics of the work environment, and such organizational variables as incentives and supervisory techniques (Campbell, Dunnette, Lawler, & Weick, 1970; Uhlaner, 1972; see also Anastasi, 1979, pp. 6–9, 46–49, 103–104, 460–461).

Structural Equation Modeling

A second example of close linkage between statistical and experimental methodology is of more recent origin. Technically known as structural equation modeling, it is a close relative of path analysis; and both are informally called causal modeling.[2] Unfortunately, there is a confusing variety of terminology in publications on this procedure. But let us see what structural equation modeling is designed to do. We all remember learning in elementary statistics that correlation does not indicate causation. If A and B are correlated, it may mean that A causes B, or B causes A, or both are caused by a third variable C, which is correlated with both. A familiar example is spurious age correlation. In a group

[2] For strict accuracy, many psychologists avoid the term "cause," aware that their empirical data demonstrate only regularity of succession between events, and such observed regularity is not necessarily absolute but is inferred from frequency of succession. Moreover, the investigator can rarely identify the mechanism whereby *A* leads to *B* or the intervening chain of events that brings about this sequence. In order to avoid philosophical arguments about causation, psychologists prefer more neutral expressions, such as independent and dependent variables, or the statements that *A* determines, influences, or affects *B* to a specified degree—if the latter can be estimated. Often the term "causal" may be used loosely, with the assumption that its limitations are understood (see, e.g., James, Mulaik, & Brett, 1982, chap. 1).

of children ranging in age from 5 to 10, we are likely to find a high correlation between height and knowledge of arithmetic; but we cannot conclude that either affects the other.

In the effort to disentangle causal relations, psychologists in the 1960s began to work with cross-lagged experimental designs (see Campbell & Stanley, 1966; Cook & Campbell, 1976, pp. 284–293). Thus, if you wanted to investigate the relative influence of attitude and ability on an individual's performance, you could, for instance, obtain measures of attitude toward math and ability in math at two points in time. Then you could compute the cross-lagged correlation between math attitude at Time 1 and math performance at Time 2, and compare it with the correlation between math performance at Time 1 and math attitude at Time 2. For a few years this seemed a neat way to assess the effects of two variables on each other, and several published studies reported results obtained by this procedure.

Before long, however, careful logical and statistical analyses revealed serious weaknesses in the use of cross-lagged correlations. Although the basic cross-lagged design was excellent, the use of simple, zero-order correlations was likely to lead to distorted results and incorrect conclusions about causal relations (Rogosa, 1980). Among the various sources of error in this procedure are the failure to take into account, first, intercorrelations between both initial and subsequent variables; second, the reliability of the variables and their stability over time; and third, the possible contribution of unmeasured variables. Structural equation modeling provides more sophisticated attempts to avoid such difficulties.

Essentially, structural equation modeling uses regression equations to predict the dependent from the independent variables in cross-lagged or other causal models. In this procedure, partial correlations are used in finding the regression coefficients, thereby utilizing all intercorrelations among the variables; both measurement and sampling errors are taken into account; and some provision is made at least to recognize the possibility of additional, unmeasured causal variables (Bentler, 1988; James, Mulaik, & Brett, 1982; Loehlin, 1987; Rogosa, 1979). Specifically, the first step is to design a model of the hypothesized causal relations to be tested. It is important that this model be based on thorough familiarity with existing knowledge about the variables and situation under investigation. The hypothesized relations should have a sound theoretical rationale. Special attention should be given to possible unmeasured variables that may themselves be correlated with measured variables in the study.

Another noteworthy feature of structural equation modeling is that causal relations are typically computed between constructs, rather than between isolated measured variables. For instance, to assess a learner's attitude toward

math, several indicators could be used, such as measures of interest, goal orientation, self-concept of math aptitude, and other relevant affective variables. The common variance among these indicators would then define a construct of the individual's attitude toward math, which can itself be related to subsequent math achievement. The use of constructs provides more stable and reliable estimates, in which the error and specific variances of the separate indicators cancel out.

The actual testing of the model is accomplished by solving a set of simultaneous linear regression equations. In causal modeling, there are usually more equations than unknowns, which permits solution for several alternative models; each model can be compared with the original, empirical correlation matrix for goodness of fit. In this process, models can be modified and the best fitting model identified. Usually, the goodness of fit is tested by Chi Square (χ^2), although in this situation the larger the χ^2 (and hence the higher the probability that the differences *did* arise by chance), the closer the fit. This fit is often expressed as a ratio between the amount of covariance explained by the model and the total amount of covariance present in the original data.

The actual computations are carried out by available and widely used computer programs.[3] But such programs do not preclude the need for thorough content knowledge; they cannot do the thinking for you. It should also be noted that the procedure I have described is a highly simplified version of one variant. There are several alternative approaches, as well as individual modifications and procedural refinements currently under consideration (see, e.g., Anderson & Gerbing, 1988; Bentler, 1990; Breckler, 1990; James, 1980; La Du & Tanaka, 1989; Mulaik et al., 1989). While still in a state of development, however, structural equation modeling is a promising procedure for combining experimental and statistical approaches. It has already been widely applied to problems in such areas as developmental, personality and social, industrial, and educational psychology.[4]

Factor Analysis

A third example of the merging of statistical and psychometric approaches is provided by the use of factor analysis in research on the organization of human behavior. The principal object of the technique of factor analysis is to simplify the description of data by reducing the number of necessary variables, or dimensions. Thus, if we find that five factors are sufficient to account for all the

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[3] Such as LISREL (Hayduk, 1988; Jöreskog & Sörbom, 1986, 1989) and EQS (Bentler, 1985).

[4] For examples of well designed studies, see Graves & Powell (1988), James & James (1989), Parkerson, Lomax, Schiller, & Walberg (1984), Shavelsen & Bolus (1982).

common variance in a battery of 20 tests, we can for most purposes substitute 5 scores for the original 20 without losing any essential information. The usual practice in this context would be to retain from among the original tests those providing the best measures of each of the factors.

All techniques of factor analysis begin with a complete matrix of intercorrelations among a set of variables, such as tests, and end with a factor matrix, that is, a table showing the weight or loading of each factor in each test. Several different methods for analyzing a set of variables into common factors have been derived. As early as 1901, Pearson pointed the way for this type of analysis, and Spearman (1904, 1927) developed a precursor of modern factor analysis. Later, Hotelling (1933) and Thurstone (1947) in the United States and Burt (1941) in England did much to advance the method. Alternative procedures, modifications, and refinements were developed by many others. The availability of high-speed computers led to the adoption of more mathematically precise and laborious techniques. Although differing in their initial postulates, most of these methods yield similar results.[5]

Today, available computer programs carry out all the necessary steps in the factor analysis of a battery of tests (or other measured variables).[6] Nevertheless, familiarity with certain major steps in the procedure helps to understand published reports of factor analytic research in psychology. Factors can be represented geometrically as reference axes in terms of which the factor loading of each test can be plotted. The tests with high loading on any one factor will tend to cluster in one region. It should be noted that the position of the reference axes is not fixed by the data, but is determined by the method of factor analysis used. The original correlation table determines only the position of the tests in relation to each other. The same points can be plotted with the reference axes in any position. For this reason, factor analysts usually rotate axes until they obtain the most satisfactory and easily interpretable pattern. This is a legitimate procedure, somewhat analogous to measuring longitude from, let us say, Chicago rather than Greenwich.

Thurstone introduced two criteria for the rotation of axes, which are still proving widely useful. The first, *positive manifold,* requires the rotation of axes to such a position as to eliminate negative weights. This condition applies particularly to aptitude tests, where a negative loading would imply that the higher the individual stands on the particular factor, the poorer will be his or her perfor-

[5] For a brief introduction to the concepts and psychometric uses of factor analysis, see Anastasi (1988, pp. 374–390); specific procedures are described in several elementary texts on factor analysis, such as Gorsuch (1983) and, at a more advanced level, Harman (1976).

[6] For simplicity, I shall henceforth use the term "test" instead of "variable" because most applications of factor analysis in psychology have dealt with tests, although all statements would apply to any kind of measured variable.

mance on the test. The second criterion, *simple structure,* means essentially that each test shall have loadings on as few factors as possible. Both of these criteria are designed to yield factors that can be most readily and unambiguously interpreted. If a test has a high loading on a single factor and no significant loading on any other, we can learn something about the nature of the factor by examining the content of the test. If, instead, the test has moderate to low loadings on six factors, it can tell us little about the nature of any one of these factors.

A useful distinction to note is that between correlated and uncorrelated factors. In the geometric representation of factors, uncorrelated factors are represented by orthogonal axes, that are at right angles to each other; correlated factors are represented by oblique axes, the angle between pairs of axes corresponding to the correlation between those factors. When the factors are themselves correlated, they can be further analyzed to yield broader, higher-order factors. Such analyses have led to the concept of a hierarchy of factors, from the narrowest and most specific variables at the base of the hierarchy to progressively broader factors at successive levels.

A single, general factor, representing what is common to a whole battery of tests, was first publicized as a "g" factor by Spearman (1927). The symbol g has become linked to Spearman's early theory of intelligence, which proposed that a single common factor could be identified across all batteries of cognitive tests, and this factor was regarded as general intelligence. This use of g has survived in loose, popular discussions of intelligence and has occasioned much confusion and misunderstanding. Such an adverse effect of factor analytic research illustrates one of the consequences of the early weakening of contact between factor analytic researchers and the mainstream of psychology.

From Primary Mental Abilities to Trait Formation

Factor analysis is of particular interest because it represents what could be described as an "emerging merger" between psychometric and experimental orientations. In its early applications to psychological research, during the first half of the twentieth century, factor analysis became increasingly dissociated from developments in other relevant areas of psychology. Its techniques came to be used more and more by test construction specialists, who were insufficiently aware of what was happening in other specialties. This period of isolation had deleterious effects on both the design of factor analytic research and on the interpretation of results.

The most conspicuous effect was a growing proliferation of factors. The one g factor identified by Spearman (1927) through the simple statistical techniques

that preceded modern factor analysis is still regarded as of prime importance by some psychometricians. Soon, however, multiple factor theories were vigorously defended by several researchers, especially in the United States. For some time, Thurstone's primary mental abilities dominated the scene. Some dozen broad group factors were identified by Thurstone and others between the 1930s and 1950s (Kelley, 1928, 1935; Thurstone, 1938; Thurstone & Thurstone, 1941; see also, Anastasi, 1988, pp. 381–390; French, 1951). Among the best known of these factors are verbal comprehension, arithmetic reasoning, spatial orientation, perceptual speed, and associative memory.

Other factor analysts then began to identify narrower group factors within the previously identified broad areas. Some, such as Guilford, suggested simple models for organizing the multitude of rapidly proliferating factors. Guilford's structure-of-intellect model, incorporating the findings of more than 20 years of research, provided a three-dimensional, box-like schema that made room for 120 or more differentiable abilities (Guilford, 1967; Guilford & Hoepfner, 1971). In commenting on this large number of abilities, Guilford argued that human nature is exceedingly complex and a few factors could not be expected to describe it adequately.

Controversies among the competing factor theorists were lively and prolonged. Each protagonist claimed to be seeking—and at least partially finding—*the* basic units of human intelligence, or thinking, or cognition. Gradually the controversies were dissipated by the proposal of comprehensive hierarchical models (Burt, 1949; Gustafson, 1989; Humphreys, 1962; Vernon, 1960). At the same time, there were methodological developments demonstrating that the different factor analytic solutions are mathematically equivalent and transposable from one to another (Harman, 1976, chap. 15; Schmid & Leiman, 1957).

It is now coming to be widely recognized that individual differences in intellectual functioning can be described at different levels of generality, from a single common factor within a whole set of variables, through increasingly narrower factors at successively lower levels. For different practical purposes, one or another level of this hierarchy is most appropriate. The trait hierarchy thus provides a comprehensive theoretical model that permits practical flexibility in test development and use for specific purposes. For example, if we want a test to aid in college admission decisions, broad factors such as verbal comprehension and numerical reasoning represent the most appropriate level; but to assess the prerequisite skills and knowledge for assignment to such occupational specialties as airline pilot, navigator, or air traffic controller, more narrowly defined sensorimotor and perceptual factors may be needed. In this connection, it may be of interest that Thurstone derived his primary mental abilities largely from data on college students, whereas Guilford began his project while developing

tests for the Air Force in World War II. Furthermore, Spearman identified his g factor in studies conducted largely with school children, among whom abilities are less differentiated than at older ages or at higher educational levels (Anastasi, 1948, 1970, 1983; Spearman, 1927).

The concentration of the early factor analysts on statistical techniques, with the neglect of psychological content and context, led to a second and more serious limitation. In interpreting the results of factor analysis, the early researchers treated the traits they identified—at whichever level of the hierarchy—as fixed, underlying causal entities, which the individual somehow possessed, which were predetermined by heredity, and which in turn accounted for that individual's observable performance. Although still surviving in popular misconceptions about human abilities and about test scores, this early view has been seriously challenged by a growing accumulation of findings in such areas as developmental psychology, behavior genetics, the experimental psychology of learning, and cross-cultural research on the composition of intelligence.[7]

More and more, researchers are now concerned, not with the discovery of rigidly fixed underlying human traits, but rather with the process of trait formation (see Anastasi, 1970, 1983, 1986, 1990, August). This is a continuing process, occurring throughout the individual's life-long learning history. What is it in an individual's learning history that led to the behavioral consistencies (or correlations) through which trait constructs are identified? One proposed mechanism involves the contiguity or co-occurrence of learning experiences, as illustrated by the development of a broad verbal factor running through all activities learned in school. Another proposed mechanism of trait formation is differential transfer of training. The breadth of the transfer effect determines whether the resulting trait is broad, like verbal comprehension, or narrow, like a specialized perceptual skill.

Concluding Comment

When dealing with human behavior, in any form and from any angle, you will encounter variability—extensive and pervasive variability. If you ignore this variability, it will come back to haunt you in the form of incorrect conclusions in basic research and wrong decisions in applied research and practice. Equally serious are the consequences of becoming totally immersed in the statistics of variability, while ignoring the psychological content and context of the behavior itself. The experimental and psychometric approaches are not only intrinsically

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[7] For more detailed treatment and references, see Anastasi (1983, 1986, 1990, August).

compatible but also mutually interdependent. Each depends upon the other for effective functioning in research design, in data analysis, and in the interpretation of results.

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Serial Averaging in Performance-Test Theory: An Interim Report

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ABSTRACT

Performance tests sample what a person can do (remember, track, aim, detect, recognize, and so on); the unit of analysis is a trial, not an item as in knowledge tests; and the person taking the test usually has at least a rough idea as to how well or poorly he or she is doing. As a result, practice effects cannot be ignored in a performance test, even when that test is very short. The present paper outlines an approach to performance tests that treats them as tasks to be learned, with a focus on reliability as a function of test length (number of trials administered). One conclusion is that low reliability in some performance tests is not corrigible by increasing test length. Results are presented for the Army Project-A, computer-administered tests.

INTRODUCTION

The Theoretical Problem of Performance Testing

The distinction between knowledge and performance testing turns on what one is trying to measure. A knowledge test samples what a person knows, a performance test what he or she can do. Plainly, this distinction is not absolute. A mathematics test, for example, may involve not only what someone knows but also what he or she can do with that knowledge. A memory task may be facilitated if a person has seen an unusual symbol before and knows what it is, say, the Greek letter *omega*. Nevertheless, most tests fall lopsidedly into one category or the other.

In a knowledge test a testee does not usually know whether he or she is right or wrong; hence, practice effects are limited to auxiliary aspects of the test (test-taking skills) and, while they exist, are not large (Messick & Jungblut, 1981; Wing, 1980). In a performance test, however, it is usually not possible to prevent a person from obtaining some idea as to how well or poorly he or she is doing. The result is that testees tend to do better on a test the more times it is administered to them (Bittner et al., 1983; Kennedy et al., 1981). In effect, each test administration becomes a trial of practice.

Psychometric theory is based on knowledge tests. The unit of analysis is an item and the order of administering the items is arbitrary. In performance testing, however, the unit of analysis is a trial and order of administration is not only nonarbitrary but often the only thing that distinguishes one trial from another. In a knowledge test it is not unreasonable to suppose that mean performance and inter-item correlations are independent of order of administration. In a performance test it is. Typically, performance improves with practice and intertrial correlations fall into a definite pattern as a function of order: the superdiagonal form (Jones, 1962).

The consequences of these differences for theory are drastic. It has long been known, for example, that inter-trial correlations, unlike inter-item correlations, may yield spurious results when subjected to conventional factor analysis (Humphreys, 1960). Also, the familiar formulae for adjusting reliability and validity for test length assume that average inter-item (inter-trial) correlation, $\bar{r}$, does not change with test length. In a superdiagonal form, as will be seen below, $\bar{r}$ definitely does change with test length. As a result, the Spearman-Brown and related formulae (Gulliksen, 1950) have to be reworked and reinterpreted if their use in performance testing is to be helpful and not misinformative.

The Practical Problem of Performance Testing

During the Second World War performance testing based on electromechanical apparatus (rotary pursuit, complex coordination, two-hand tracking, and the like) was widely and successfully used in military selection, especially for pilot training (Melton, 1947). The equipment, however, was heavy, bulky, difficult to maintain, and more difficult to replace. By the late 1950s all three military services had abandoned performance testing in favor of paper-and-pencil tests exclusively. Then in the late 1970s the advent of microcomputers reopened the possibility of performance testing, this time with equipment that occupied little space, did not break down frequently, and was easily replaced when it did. At the same time experimental psychology was undergoing a revolution of its own, as the discipline's central focus shifted from learning theory to cognition and information-processing. The joint effect of these two developments was a new generation of cognitively oriented, microcomputer-based performance tests. The computer-administered tests in Project A are cases in point (Eaton, Hanser, & Shields, 1986; Peterson, 1987).

Unfortunately, all has not been clear sailing for this new generation of performance tests. The most serious problem has been that many tests have low reliabilities (Kyllonen, 1985). Predictive validities against real-world criteria are still sparse, but it seems likely that oftentimes they will also be low. An appropriate response to these difficulties involves more than making and trying out

Table 1.—Hypothetical Correlations, with the Average Correlation ($\bar{r}_i$) and Reliability (R_i) up to a Given Trial

	Trial						
Trial	1	2	3	4	5	6	7
1	—	.80	.65	.50	.35	.20	.05
2		—	.80	.65	.50	.35	.20
3			—	.80	.65	.50	.35
4				—	.80	.65	.50
5					—	.80	.65
6						—	.80
7							—
$\bar{r}_i$	—	.80	.75	.70	.65	.60	.55
R_i*	.800	.889	.900	.903	.902	.900	.895

* R_i ($i \geq 2$) is calculated from $\bar{r}_i$ using the Spearman-Brown formula; when $i = 1$, $R_1 = \bar{r}_2$.

new tests. What is needed is a theory of performance tests, that is, an approach to test construction and validation that recognizes and capitalizes upon the distinctive properties of performance tests.

Approach

Superdiagonal form is one of the best established regularities in human learning (Jones, 1962, 1969). It refers to the essentially universal tendency for trials of practice to correlate more strongly the closer they are together in the practice sequence. Table 1 presents a hypothetical example. The correlation between neighboring trials is .80. When there is one intervening trial, the correlation drops to .65. When two trials intervene, the correlation drops to .50. The weakest correlation is between the first and last trials in the sequence, in the example, .05. In a motor-skills experiment, where each data point typically represents as much as 20 min. of practice, the superdiagonal pattern is always present and, in large samples, usually quite regular. In correlations among individual trials of practice, as in performance testing, the pattern may be very irregular. Almost always, however, if correlations are averaged over groups of consecutive trials, the pattern can still be seen.

Table 1 illustrates another point, this one directly relevant to performance testing. In conventional test theory the Spearman-Brown (S-B) formula (Gulliksen, 1950) states that the reliability of a test *i* units in length

$$R_i = \frac{iR_1}{1 + (i - 1)R_1},$$

where R_1 is the reliability of a test of unit length. When $i \geq 2$, R_1 is taken as the average correlation among the *i* units, that is, $\bar{r}_i$. The first row at the bottom of

the table shows this average correlation for the first two trials, the first three, out to all seven trials. As is clear from the table, these averages decrease from the first to the last trial. Since the correlations decrease along any row to the right, each new trial adds to the average a column of correlations lower than those already in it; hence $\bar{r}_i$ drops a notch.[1]

Low reliability in a knowledge test is corrigible. It may be laborious to do, but in principle one can always lengthen the test, while maintaining the same average inter-item correlation, and thereby improve its reliability. In a performance test, however, $\bar{r}_i$ does not remain the same as the test is lengthened; it decreases. The bottom row in Table 1 gives R_i as calculated by the S-B formula for i = 1, . . . , 7. As i increases, $\bar{r}_i$ both decreases and is more strongly amplified by the S-B formula. The amplification, however, is negatively accelerated while, in this example, the decrease in $\bar{r}_i$ proceeds at a constant rate. The upshot is that R_i increases sharply at first, reaches a maximum (at i = 4), and then decreases gently. In this case, therefore, reliability would not be improved by lengthening the test. In fact, the test could be shortened to 4 trials with no loss of reliability.

The superdiagonal pattern in Table 1 is perfectly regular, that is, constant within any given diagonal and regularly decreasing between diagonals. As we have seen, however, it nevertheless tends to yield reliabilities that increase to an optimum and then decrease gently. This tendency may be reinforced by other considerations. As the number of trials increases, some testees may become fatigued or lose concentration; and performance in the presence of fatigue and wavering attention tends to be fitful and erratic. These changes introduce novel variance not present in earlier trials of practice. The effect is to produce a drop in correlational level late in practice and, therefore, to bring about a forward optimum earlier than it would have occurred in a perfectly regular pattern.

In practice, reliability as calculated by the S-B formula from a series of acquisition (test) trials is less interesting than temporal stability—that is, the correlation between test and retest over appreciable periods of time (months or years), where a person's score is his or her average performance over the first i trials at test or retest. In a single test series a perfectly regular superdiagonal pattern, like the one in Table 1, suffices to produce a forward optimum (that is, a maximum prior to the last trial), provided the gradient away from the superdiagonal is steep and the series is long enough. When testees are tested in two well-separated series of trials, the conditions are somewhat different. Specifically, the matrix of test-retest correlations decomposes into three submatrices: the correlations among test trials, the correlations among retest trials, and the square matrix of correla-

[1] As given above, the S-B formula assumes that all trials have the same variance. In the section on reliability this restriction is relaxed, by restating the formula in terms of variances and covariances.

tions between test and retest trials. The first two submatrices both tend to follow superdiagonal form, and the average correlation between test and retest trials often decreases as i increases. As a result, the average correlation in all three submatrices decreases as i increases, and temporal stability rises to an optimum and decreases gently thereafter. Like low reliability, therefore, low temporal stability is not necessarily corrigible by increasing test length. Moreover, when temporal stability can be improved by increasing test length, the gain may be sharply limited. An optimum may be reached after only a modest increase in test length, and the optimal value may be well short of unity.

Forward optima in reliability and temporal stability have important implications for the construction of performance tests. If a test shows a forward optimum in stability, the implication is that lengthening the test will not improve its stability. It is true that if the test was lengthened, stability, after decreasing for a stretch of trials, might start increasing again to a second optimum. To date, however, I have not seen any such second increase. One does see small departures from increasing, level, or decreasing curves but not a second increasing trend in a curve's general direction. If, however, an optimum once reached will not be exceeded or, in the worst case, not exceeded by much, then lengthening the test will not improve its temporal stability.

If a test has not reached an optimum or asymptote with the number of trials given, it is possible to project where the optimum would fall if a test series was lengthened. This projection is based primarily on extrapolating the course of average correlations, either among test (or retest) trials or between test and retest trials as the test lengthens. Such projections are, of course, no better than the extrapolations on which they are based. Still, forward averages provide an empirical basis for decisions regarding the length of a performance test. It can tell us when a series of trials is already long enough, whether it might be shortened without loss of stability, how much it would have to be lengthened to reach an optimum, and how much of a gain could be realized by so lengthening it.

Once a test has been constructed, it may be used to predict performance on numerous external criteria. At this point the issue is no longer test construction (test length) but test scoring. The usual practice is to average all trials given. Forward averages, however, may also be correlated with an external criterion. When they are, the correlations (predictive validities) always rise at first and sometimes reach an optimum, after which they decrease. It has long been recognized that the differential content of a task, the abilities involved in it, may change with practice (Ackerman, 1987; Fleishman & Hempel, 1954) and that, as they do, the relation of the practiced task to an external criterion may also change. There is, therefore, no reason to be surprised if the average of the first i trials sometimes predicts a criterion better than the average of all trials given.

If, however, a forward optimum in predictive validity exists, then averaging only those trials up to and including the optimum will yield a higher predictive validity than the usual practice. Since the differential composition of a test may change with practice and an external criterion may be most strongly related to those components of a test that predominate at the beginning (say) or in the middle of a practice series, stability and validity optima do not necessarily fall on the same trial. For the same reasons, the optimal forward average for purposes of prediction may vary from one external criterion to another.

Averaging from the first trial forward is only one way to generate a series of averages from a series of test trials. Another way is to average from the last trial backwards. The temporal stability of backward averages can, of course, be calculated and sometimes a maximum occurs before the first trial is reached (a backward optimum). Backward optima, however, are not informative about how changes in test length might affect temporal stability. A forward average of, say, 5 trials retains its meaning (refers to the same trials) regardless of how many trials are ultimately given. A backward average of 5 trials, however, refers to trials 6–10 if 10 trials are given and to trials 11–15 if a total of 15 trials is given. A backward average changes its meaning when the total number of trials changes. As a consequence, no conclusions regarding changes in test length can be drawn from a backward stability optimum.

Backward averages may also be correlated with an external criterion. When they are, the correlation (predictive validity) rises at first and may reach an optimum prior to the first trial. In these cases, as in the corresponding cases involving forward optima, averaging only those trials up to and including the optimum (following it in the practice series) yields a higher predictive validity than averaging all trials given. Backward optima are especially helpful in improving a test's validity when a forward validity optimum also exists.

One final point should be noted. It may happen that predictive validity takes different values in different subsets of trials. Where this happens, one may restructure the test to consist exclusively of subsets with high validities, very much as in conventional item analysis. Once such a restructuring is done, however, it should be followed (a) by forward averaging to determine the optimal test length for reliability and temporal stability, and (b) by both forward and backward averaging to determine optimal scoring for predictive validity.

Altogether, serial (forward or backward) averaging has four areas of application in performance-test theory: reliability, temporal stability, predictive validity, and subset analysis. The present paper reports results obtained using the computer-administered tests in Project A (see below). It is an interim report for two reasons. First, results are presented for reliability only. Second, validation results only are presented; a cross-validation is currently underway.

Table 2.—Number of Test Trials and Total Length of Time Required, Including Instructions and Inter-Trial Intervals, for the 10 Project-A, Computer-Administered Tests

Test	Number of Trials (n)	Total Time (min.)
Simple Reaction Time	10	2
Choice Reaction Time	30	3
Short-Term Memory Test	36	7
Target Tracking 1	18	8
Perceptual Speed & Accuracy	36	6
Target Tracking 2	18	7
Number Memory	28	10
Cannon Shoot	36	7
Target Identification	36	4
Target Shoot	30	5

Tests, Testees, and Procedures

The Project-A Tests

Project A is a large, multi-year effort to improve the Armed Forces Vocational Aptitude Battery (Eaton, et al., 1986; Peterson, 1987). Included in this effort are 10 newly developed, computer-administered performance tests. Brief descriptions of the 10 tests are given below. The tests are administered in the order described. Table 2 shows the number of trials a person receives on each test and, approximately, the total length of time each test requires.

Simple reaction time. The testee is instructed to place his or her hands in the ready position. When the word YELLOW appears in a display box, the testee strikes the yellow key on the test panel as quickly as he or she can. The dependent measure is average time to respond.

Choice reaction time. This test is much the same as Simple Reaction Time. The major difference is that the stimulus in the display box is BLUE or WHITE (rather than YELLOW), and the testee is instructed to strike the corresponding blue or white key on the test panel. The dependent measure is average time to respond on trials in which the testee makes the correct response.

Short-term memory. A stimulus set, consisting of 1, 3, or 5 letters or symbols, is presented on the display screen. Following a delay period, the set disappears. When the probe stimulus appears, the testee must decide whether or not it was part of the stimulus set. The dependent measure is average time to respond on trials in which the testee makes the correct response.

Target tracking 1. This is a pursuit tracking test. The testee's task is to keep a crosshair centered within a box that moves along a path consisting exclusively of vertical and horizontal lines. The dependent measure is the average distance from the crosshair to the center of the target box.

Perceptual speed and accuracy. This test measures a testee's ability to compare rapidly two stimuli presented simultaneously and determine whether they are the same or different. The stimuli may contain 2, 5, or 9 characters and the characters may be letters, numbers, or other symbols. The dependent measure is average time to respond on trials where the testee's response is correct.

Target tracking 2. This test is the same as Target Tracking 1, except that the testee uses two sliding resistors instead of a joystick to control the crosshair. The dependent measure is the same as in Target Tracking 1.

Number memory. The testee is presented with a number on the computer screen. When the testee presses a button, the number disappears and another number appears along with an operation term, e.g., "Add 9" or "Multiply by 3". Another press of the button and another number and operation term are presented. This procedure continues until finally a solution to the problem is presented. The testee must then indicate whether the solution presented is correct or incorrect. The dependent measure is total time to respond on trials in which the testee correctly identifies the solution presented as correct or incorrect.

Cannon shoot. The testee's task is to fire a shell from a stationary cannon so that it hits a target moving across the cannon's line of fire. The dependent measure is a deviation score indicating the difference between time of fire and optimal fire time (for example, a direct hit yields a deviation score of zero).

Target identification. The testee is presented with a target and three stimulus objects. The objects are pictures of tanks, planes, or helicopters. The target is the same as one of the three stimulus objects but rotated or reduced in size. The testee must determine which of the three stimulus objects is the same as the target object. The dependent measure is average time to respond on trials in which the testee makes the correct response.

Target shoot. The testee's task is to move a crosshair over a moving target and then press a button to fire. The dependent measure is distance from the crosshair to the center of the target when the testee fires.

The Criterion Task

In addition to the Project-A tests, each person participating in the study was administered a criterion task. This task was Anti-Aircraft, game #1 in the Atari Air-Sea Battle cartridge (CX-2624). In this game the individual controls a gun placed two thirds of the way from left to right at the bottom of a television screen. Four different kinds of aircraft traverse the screen above the gun, in different numbers, at different speeds and altitudes, and from left to right or vice versa. The purpose of the game is to shoot down as many aircraft as possible in a 2-min.-and-16-sec. game. The control devices are a joystick for positioning the gun and a button for firing the missile. The missile itself was the smaller of two

possible sizes (difficulty position "A"). The dependent measure is number of aircraft shot down per game. Anti-Aircraft is a complex psychomotor skill with a high performance-ceiling. No testee comes close to reaching the maximal possible performance with the amount of testing given.

Participants and Procedures

The participants in the study were 102 central Pennsylvania undergraduate college students, 50 men and 52 women. Each student was administered the Project-A tests at the start of the fall semester (September–October) and then again four months later at the start of the spring semester (January–February). The Project-A tests were taken in a single sitting that lasted between 45 and 75 min. depending on how quickly the student responded to the tests and the instructions that preceded them. The entire administration, both test and retest, instructions as well as the tests themselves, were computer controlled.

In the fall, following the Project-A tests, each student was administered five sessions of Anti-Aircraft, each session consisting of seven games, for a little more than 16 min. of playing time. All five sessions were completed within a ten-day period, with no more than two sessions taking place on a given day. In the spring semester, again following the Project-A tests, each student was given three sessions of Anti-Aircraft with the same number of games per session and the same conditions as to distribution as in acquisition.

RESULTS

Comparison with Army Data

Table 3 compares the present results with those collected by Peterson, Hough, Dunnette, Rosse, Houston, Toquam, and Wing (1990) in overlapping samples of Army enlisted people ranging in number from 8,892 to 9,269 for different tests. The college students performed better on all tests, but some of the differences were sizable whereas others were small. The largest differences were for the two memory tests, in both cases half a standard deviation (SD) or more.[2] The next largest differences were for the two *perceptual* tests (Perceptual Speed & Accuracy and Target Identification), approximately .4 SD. The differences for Choice Reaction and the two tracking tests were approximately .33 SD, while those for Simple Reaction and the two aiming tests (Cannon Shoot and Target Shoot) were less than .2 SD. All differences except the last three were significant

[2] "Standard deviation" refers here to the square root of the pooled within-group variance.

Table 3.—Comparison of Soldier and Student Results on the Project-A Tests*

Test/Measure	Testee	*M*	*SD*	Reliability	Temporal Stability
Simple Reaction**	Soldier	31.84	14.82	.88	.23
(mean dec. time)	Student	29.38	4.94	.88	.50
Choice Reaction	Soldier	40.83	9.77	.97	.69
(mean dec. time)	Student	36.54	6.48	.97	.77
Short-Term Memory	Soldier	87.72	24.03	.96	.66
(mean dec. time)	Student	70.98	17.43	.97	.69
Target Tracking 1	Soldier	2.98	0.49	.98	.74
(mean ln dist. + 1)	Student	2.77	0.43	.98	.87
Perceptual S & A	Soldier	236.91	63.38	.94	.63
(mean dec. time)	Student	202.42	47.10	.95	.73
Target Tracking 2	Soldier	3.70	0.51	.98	.85
(mean ln dist. + 1)	Student	3.45	0.52	.98	.91
Number Memory	Soldier	160.70	42.63	.88	.62
(final resp. time mean)	Student	118.39	27.89	.91	.69
Cannon Shoot	Soldier	43.94	9.57	.65	.52
(mean abs. time disc.)	Student	43.80	8.52	.51	.53
Target Identification	Soldier	193.65	63.13	.97	.78
(mean dec. time)	Student	163.84	45.08	.95	.71
Target Shoot	Soldier	2.17	0.24	.74	.37
(mean ln dist. + 1)	Student	2.14	0.20	.71	.70

* All times are in hundredths of a second. Logs (ln) are natural logs.

** Simple Reaction in the Army battery had 15 trials; the students were given only 10 trials. Number of trials in the remaining tests were the same in the soldier as in the student battery. The numbers are shown in Table 2.

at the $p = .01$ level as determined by t tests. These differences were broadly what one would expect, i.e., the more *cognitive* a test, the larger the difference in favor of the students.

Variabilities were greater in the soldier than in the student data, except for Target Tracking 2, but not greatly so, except for Simple Reaction. The variance of Simple Reaction was nine times as large among the enlisted people as among the students. Simple Reaction was the first test in the battery, and there may have been some confusion among the Army testees as to what they were supposed to do. If so, it would explain the high variability of the Simple Reaction Test in the Army data.

The column headed *Reliability* contains, for the soldier data, odd-even correlations corrected for test length by the Spearman-Brown formula and, for the student data, Spearman-Brown projections from the average correlation involving all trials. Thus, both figures make use of all trials administered and both use the Spearman-Brown formula. The correspondence between the two sets of figures is startlingly close.

The column headed *Temporal Stability* contains two-week test-retest correlations for the Army data and four-month test-retest correlations for the student data. Again, an individual's score on any given test is the average of his or her scores on all trials administered. Temporal stability was better among students

than soldiers for all tests except Target Identification and may have been better even for Target Identification, given that the retest interval was eight times longer in the college than in the Army sample. There are at least four procedural differences that may have contributed to better stability among students. First, of course, was the difference in population: college students versus enlisted people. Second, the sex ratio in the college sample was essentially 50-50, whereas males predominated in the Army sample. Third, the tests were administered to the college students by a single, very experienced person, whereas the Army data were collected at many places by many people, some of them not experienced test administrators. Fourth, the students were tested one or two at a time, whereas the soldiers were tested in groups of as many as two or three dozen at a time.

In general, the differences between the two arrays of stability results were not large. The low stability for Simple Reaction in the Army data was probably related to that test's high variability. No obvious explanation exists for the low stability of Target Shoot in the Army sample, except perhaps that it was the last test in the battery.

Reliability

Figure 1 presents reliability results for the Simple Reaction Test. The average correlation ($\bar{r}_i$) tended to decrease sharply from the 2nd to the 10th trial. A straight line has been fitted to those nine points and extended out to trial 25. The correlations R_i are Spearman-Brown projections for a test of length, i, given that a test of unit length has reliability, $R_1 = \bar{r}_i$. The smooth curve was obtained by applying the Spearman-Brown formula to corresponding points, $\bar{r}'_i$, on the regression line. The smooth curve has also been extended to trial 25. Such a curve reaches a maximum at

$$i^* = \frac{(1 - a) - \sqrt{1 - a}}{b},$$

where a and b are the intercept and slope, respectively, of the regression line. In this case i^* was estimated to occur at about the 19th trial. The reliability of Simple Reaction could be improved only slightly by lengthening the test; doubling the number of trials would increase reliability by .02 but still leave it at .897, well short of unity. More than doubling the number of trials would be counterproductive.

Figure 1 can be improved in two key respects. First, the linear regression line in Figure 1 was obtained by weighting the $\bar{r}_i$ equally. The $\bar{r}_i$, however, are based on very different numbers of correlations. For example, $\bar{r}_2$ is based on only one correlation, whereas $\bar{r}_{10}$ is based on 45. It would make sense on strictly statistical

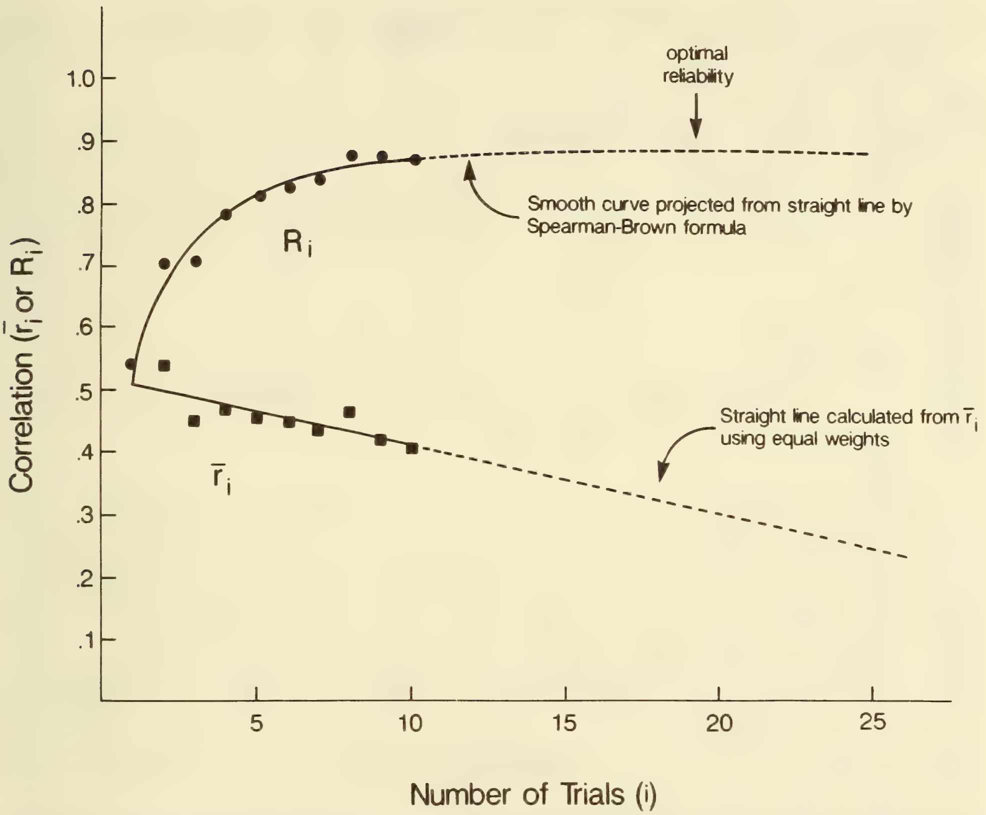

Fig. 1. Average correlation and Spearman-Brown reliability up to trial *i* for Simple Reaction Time. The straight line was calculated weighting all average correlations equally.

grounds to weight the $\bar{r}_i$ for the number of correlations on which each one is based. It makes especially good sense when one remembers that the main purpose in fitting the regression line is to predict the course that $\bar{r}_i$ will follow beyond the total number of trials administered (n). The $\bar{r}_i$ usually follow a decreasing, negatively accelerated course. Therefore, the best prediction of where $\bar{r}_i$ will lie when $i > n$ is the slope of the $\bar{r}_i$ curve, not overall, but just before the administered sequence reaches its end. Weighting the $\bar{r}_i$ for the number of correlations on which each one is based effectively approximates such a slope. The early points are heavily discounted in favor of the last few points. The resulting line is almost always shallower than the one obtained by equal weighting of the $\bar{r}_i$. Hence, the number of trials for optimal reliability, i^*, is increased (pushed further out).

The second key improvement concerns how to estimate R_1. The estimation based on $\bar{r}_i$ assumes that all trials have equal variances. If this is not so (and it never is), the appropriate estimate becomes

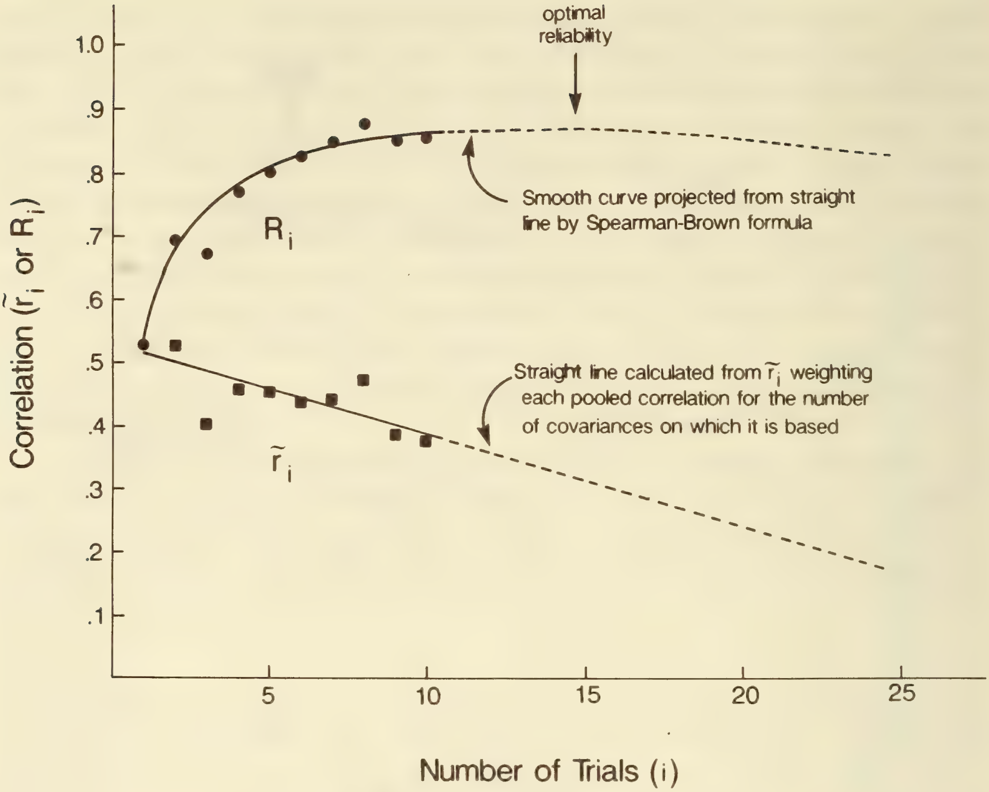

Fig. 2. Pooled correlations ($\overline{cov}/\overline{var}$) and Spearman-Brown reliability up to trial *i* for Simple Reaction Time. The straight line was calculated by weighting each pooled correlation for the number of covariances on which it is based.

$$R_1 = \tilde{r}_i = \frac{\overline{cov}_i}{\overline{var}_i},$$

where $\overline{cov}_i$ and $\overline{var}_i$ are, respectively, the averages of all covariances and variances up to trial *i*. In effect, $\tilde{r}_i$ weights the correlations for the variances involved in them. Correlations between trials with large variances count for more than correlations between trials with small variances. This improvement has no systematic effect on i^*. Sometimes it increases i^* and sometimes, as in the case of the Simple Reaction Test, it decreases i^*.

Figure 2 presents the reliability results for the Simple Reaction Test, using $\tilde{r}_i$ and a weighted regression line. The net effect is to decrease i^* to 14.8 and to reduce the optimal reliability to .874.

Table 4 presents reliability results for all ten tests, using $\tilde{r}_i$ and a weighted regression line. For two tests (Perceptual Speed & Accuracy and Target Tracking

Table 4.—Reliability Results for the Project-A Tests, Using Pooled Averages ($\bar{r}_i$) and Weighted Regression

Test	No. of Trials	Slope ($b \times 10^3$)	Optimal No. of Trials (i^*)	Projected Reliability: At Trial n (R'_n)	Projected Reliability: At Trial i* (R'_{i^*})
Simple Reaction	10	−14.42	.864	14.8	.874
Choice Reaction	30	−1.05	.963	195.3	.988
Short-Term Memory	36	−1.16	.952	159.4	.977
Target Tracking 1	18	−2.46	.983	100.3	.992
Perceptual S & A	36	+0.16	.939	∞	1.000
Target Tracking 2	18	+1.69	.984	∞	1.000
Number Memory	28	−1.21	.869	96.2	.921
Cannon Shoot	36	−1.09	.499	29.9	.510
Target Identification	36	−0.50	.947	310.9	.987
Target Shoot	30	−1.82	.701	33.8	.704

2) the regression line had positive slope ($b > 0$). In those two cases, therefore, i^* was indefinitely large and there was no optimal reliability short of unity. In the other eight tests the slopes were negative, i^* finite, and optimal reliability some value less than unity. In five of these eight cases, however, i^* was very large and, with the exception of Number Memory, the projected optimal reliability, R'_{i^*}, was close to unity. In one case (Cannon Shoot), however, $i^* < n$, i.e., the number of trials for optimal reliability was less than the number administered. In such a case reliability cannot be improved by lengthening the test. In fact, the test could be shortened without reducing optimal reliability. In two tests, Target Shoot and Simple Reaction Time, i^* lay less than five trials ahead of where the administered sequence stops. In both cases little would be gained by increasing the number of trials and optimal reliability was well short of unity.

Comment

At one level, serial averaging is a prosaic data-processing procedure. It is based, however, on a view of performance testing that departs fundamentally from classical test theory. The gist of that departure is not to replace one theory with another but to hybridize classical test theory with the study of individual differences in skill acquisition and retention. This hybrid is more a matter of approach and concept than content. Conventional test theory is purely structural; time has no place in it. The study of skill acquisition and retention, however, is processual; everything in it is embedded in time and is, therefore, temporally ordered. Large parts of this structural-processual hybrid have been taken over from classical theory. Other parts, however, come from the processual component in the hybrid: for example, the treatment in terms of trials, the

centrality of order, or the recognition and use of established regularities such as superdiagonal form. The overall approach is open, moreover, to further imports from the study of skill acquisition. Distribution and transfer effects, reminiscence, many possible results from cognitive science, may ultimately find a place in a theory of performance testing hybridized to include performance as well as test phenomena.

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Space Adaptation Syndrome: Multiple Etiological Factors and Individual Differences

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ABSTRACT

Space motion sickness is a significant operational concern in the American and Soviet space programs. Nearly 70% of all astronauts and cosmonauts are affected to some degree during their first several days of flight. It is now beginning to appear that space motion sickness like terrestrial motion sickness is the consequence of multiple etiological factors. As we come to understand basic mechanisms of spatial orientation and sensory-motor adaptation we can begin to predict etiological factors in different motion environments. Individuals vary greatly in the extent to which they are susceptible to these different factors. However, individuals seem to be relatively self-consistent in terms of their rates of adaptation to provocative stimulation and their retention of adaptation. Attempts to relate susceptibility to motion sickness during the microgravity phases of parabolic flight maneuvers to vestibular function under 1G and 0G test conditions are described.

Introduction

Space motion sickness is a significant operational problem in both the American and Soviet space programs. It affects nearly 70 percent of all astronauts and cosmonauts (Jennings, Davis & Santy, 1988). Its onset can be as early as an hour after insertion into orbit or microgravity and as long as many hours or even a day or two. Usually, it is self-limiting and largely abates by Mission Day 3 so that normal or near normal activities are possible. Astronauts also vary considerably in terms of how severely they experience space motion sickness. They report that keeping the head still can prevent or suppress symptoms, but of course this is usually not practical under operational conditions. In general, the symptoms are much like those of motion sickness experienced on Earth and can include drowsiness, nausea, vomiting, apathy and the wide constellation of signs and symptoms characteristic of motion sickness.

A key concern in the space program has been to identify the primary etiologi-

cal factors in space motion sickness in order to provide the basis for developing tests of susceptibility and adaptation or training procedures for decreasing susceptibility. This has proven to be a very difficult task. One of the reasons is that investigators in the field, at least initially, approached space motion sickness as if it were a unitary phenomenon arising from a single factor associated with being in a weightless environment. For example, early on it was thought that the redistributions of body fluid associated with the absence of hydrostatic pressure in the circulatory system in 0G were responsible (Gibson, 1974; Kerwin, 1974; Thornton, Hoffler & Rummel, 1974). The fluid shift was thought to alter the pressures within the organs of equilibrium of the inner ear. This notion was appealing because of its simplicity, but experimental manipulations of fluid shift magnitudes on Earth had no discernible effect on motion sickness susceptibility during provocative stimulation (Graybiel & Lackner, 1977).

One of the features which has characterized motion sickness research over the years has been the difficulty of making generalizations about an individual's susceptibility across different motion exposure conditions, even ones involving ostensibly similar patterns of stimulation. Our work concerning space motion sickness and individual differences may enable us to better understand the reasons for this variability. We have come to the conclusion that a given exposure situation may be provocative for a variety of reasons and that individuals vary in their susceptibility to different potentially provocative aspects of these situations. Put differently, individual differences in susceptibility may not be simply reflecting a greater or lesser amount of "noise" but rather be pointing to the complexities of the test situation and of spatial orientation mechanisms. This means that in developing assessment and adaptation procedures "individual differences" are pointing to the need to assess and train on multiple dimensions.

Our own work represents an attempt to understand why astronauts become motion sick during exposure to microgravity, and what kinds of procedures can be employed to prevent or attenuate sickness. In some of our first studies, we looked at susceptibility to motion sickness in a variety of different "motion environments" including parabolic flight (Lackner & Graybiel, 1983, 1986, 1987) where periods of weightlessness and high force alternate, and during exposure to provocative vestibular stimulation in the form of repeated impulsive decelerations from constant velocity rotation (Graybiel & Lackner, 1980; Lackner & Graybiel, 1979). Half of the individuals also participated in studies in a slow rotation room, where the stressor is generated by head movements; if the head is kept still, motion sickness does not result. In each of these different situations, the individuals had participated on multiple occasions. Thus, it was possible to measure their initial susceptibility as well as their acquisition and retention of adaptation to some extent, and to compare these values for the

different test conditions for each individual as well as collectively. The general conclusion we came to from these studies was that despite great individual differences in susceptibility, persons who had a high rate of adaptation and a high level of retention of adaptation in one situation, regardless of initial susceptibility, showed a similar pattern of adaptation rate and retention in other situations. Moreover, in these experiments, the performance on the impulsive vestibular stimulation task seemed to be most predictive of acquisition and retention in the other situations (Graybiel & Lackner, 1983).

The observations to be described below represent a variation on this theme. We sought to develop tests that would allow us to relate susceptibility to motion sickness in parabolic flight with alterations in vestibulo-ocular function. We took this approach because perhaps the single most important finding in the motion sickness literature is that without exception persons who lack labyrinthine function cannot be made motion sick (Graybiel & Johnson, 1963; Money & Friedberg, 1964). Moreover, there is also strong evidence that individuals with partial loss, e.g., half-sided destruction of function, are less susceptible to motion sickness than normal persons after recovery from the acute loss (Graybiel & Johnson).

We also wanted to use test procedures in which we would be able to quantify quite precisely the stimulus delivered and the responses obtained for functionally relevant situations. In addition, we wanted to have some conditions that would incorporate voluntary head movements. Our approach was to use sudden stops from constant angular velocity rotation to deliver step stimuli to the semicircular canals and in some trials to have the individual voluntarily make a head tilt after the trials. On Earth, such post-rotary head tilts will suppress or attenuate the nystagmus elicited by a velocity step, this suppression is often referred to as dumping (Raphan, Cohen & Matsuo, 1977). It is thought to be related to the re-orientation of the linear acceleration sensitive otolith organs of the inner ear to the force of gravity.

Dumping is thought to represent an abolishment of velocity storage (Raphan, Cohen & Matsuo, 1977). Figure 1 illustrates the concept of velocity storage. The post-rotary response to vestibular stimulation considerably outlasts the peripheral response of the semicircular canals. For example, the time constant of the human horizontal semicircular canals is computed on allometric considerations to be about 8 or 9 s. By contrast, the time constant of post-rotary nystagmus is often 15 s or more. This is because there are thought to be two signals driving the eyes, one directly from the semicircular canals and one a "velocity storage" signal from a brain stem integrator which receives a copy of the canal signal. Dumping is thought to be an attenuation of velocity storage.

Interestingly, too, in virtually all terrestrial situations in which dumping oc-

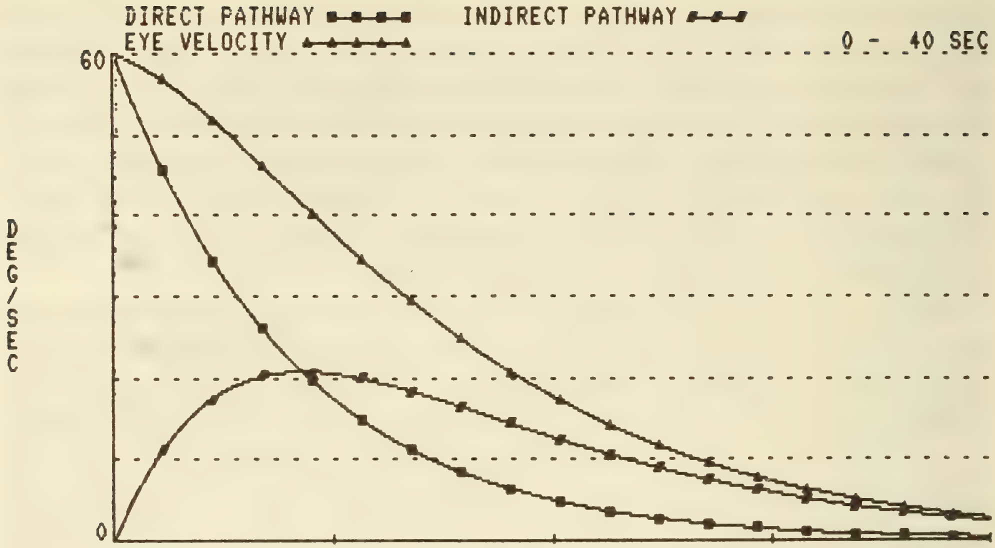

Fig. 1. Simulation of the slow phase velocity of vestibular nystagmus elicited by a sudden stop from 60°/s constant velocity rotation, according to the model of Raphan, Cohen, and Matsuo (1977). In this model, eye velocity is dependent on two factors: 1) semicircular canal activity which is conveyed by the direct pathway, and 2) the activity of a brain stem integrator which integrates a copy of the canal signal, this "velocity storage" is then conveyed by the indirect pathway. The combined direct and indirect pathway activity determines eye velocity.

curs (i.e., in which velocity storage is continuously suppressed or in which it is dumped by a head movement), motion sickness also is common. In fact, we do not know of situations involving dumping which are not provocative. However, people can become motion sick in situations where dumping is either empirically lacking or theoretically not expected; this will be discussed later with regard to implications for multiple etiological mechanisms. In these experiments we attempted to relate individual differences in motion sickness susceptibility during head movements in parabolic flight with individual differences in peripheral vestibular mechanisms, velocity storage, and dumping.

Methods

The experiments were carried out during parabolic flight maneuvers (Figure 2) in which the gravitoinertial resultant force varied from 0G to 1.8G, with the high and low force phases each lasting about 25 s (DiZio & Lackner, 1988). Our observations were carried out during these periods and during straight and level flight at 1G. Fifteen individuals who ranged in age from 18 to 45 took part. Each had passed an FAA Class II flight physical and was without known sensory

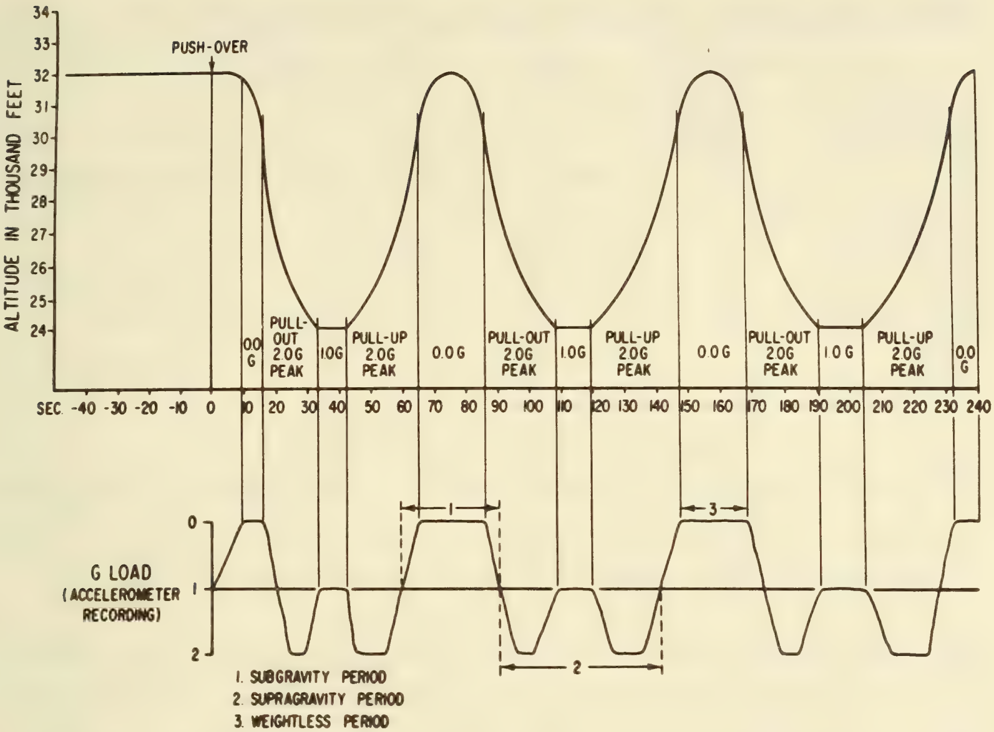

Fig. 2. Schematic illustration of the flight profile of the KC-135 aircraft during parabolic maneuvers and the associated alterations in gravitoinertial force level.

or motor abnormalities (except several wore spectacles). They were not medicated during the experiments.

On any given flight day, the participants received only six trials, which were balanced across 0G, 1G and 1.8G, head movements and no head movements. On a given flight day, 40 parabolas would be flown and a person would be tested in the first, second, third, or fourth set of ten. During a given flight week there would be four consecutive days of 40 parabola flights. A particular individual would receive the vestibulo-ocular tests on, at most, two of these days. Each person participated in multiple flight weeks, usually separated by several months or more.

Six of the individuals also participated in later observations in which they were tested early and late in flight with sudden stops during the course of a single 40-parabola flight to determine whether adaptation or habituation would occur.

Motion sickness susceptibility was assessed during an individual's first two days of a parabolic flight week, some persons were assessed on multiple occasions. On the first of these days, the individuals sat in an aircraft seat restrained by a lap belt, they were permitted normal vision and were free to move their

Table 1.—Diagnostic Categorization of Different Levels of Severity of Acute Motion Sickness

Category	Pathognomonic 16 Points	Major 8 Points	Minor 4 Points	Minimal 2 Points	AQS* 1 Point
Nausea syndrome	Vomiting or retching	Nausea† II, III	Nausea I	Epigastric discomfort	Epigastric awareness
Skin		Pallor III	Pallor II	Pallor I	Flushing/Subjective warmth ≥ II
Cold sweating		III	II	I	
Increased salivation		III	II	I	
Drowsiness		III	II	I	
Pain					Headache ≥ II
Central nervous system					Dizziness Eyes closed ≥ II Eyes open III

Levels of Severity Identified by Total Points Scored

Frank Sickness (S)	Severe Malaise (M III)	Moderate Malaise A (M IIA)	Moderate Malaise B (M IIB)	Slight Malaise (M I)
≥16 points	8–15 points	5–7 points	3–4 points	1–2 points

* AQS = Additional qualifying symptoms. †III = severe or marked, II = moderate, I = slight.

head and eyes. On the second day, they were free to move about the aircraft except for brief participation in tests not involving rotation or provocative stimulation. Throughout these two flight periods, the individuals were carefully monitored for symptoms of motion sickness after every 10 parabolas using the symptom identification system (Table 1) developed by Graybiel and his colleagues (Graybiel, Wood, Miller & Cramer, 1968). We averaged the number of motion sickness points accumulated on the four sets of parabolas on a given day, and the scores for an individual's two days were averaged for a final score.

For the vestibular tests, the blindfolded participants were rotated in a servo-controlled chair about the z-axis of the body, at a constant velocity of 60°/s for at least 60 s. They were brought to a sudden stop within 3 s after a transition into the desired G level. In trials involving head movements after the stop, the individual voluntarily moved the head backwards, the head movement being mechanically confined to the pitch plane and to an amplitude of 40°. Appropriate instrumentation was used to record G level, rotational velocity, eye movements, and head movements. Appropriate procedures (DiZio & Lackner, 1988) were used to compute the step gain and dominant time constant of decay of vestibular nystagmus.

Results

Table 2 shows a rank ordering of the individuals according to their susceptibility to motion sickness along with the step gain of their vestibulo-ocular reflex to

Table 2.—Motion Sickness Susceptibility in Parabolic Flight, Step Gain of the Vestibulo-Ocular Reflex Following Sudden Stop Stimulation (SS), and Modification of Step Gain by Gravitoinertial Force Level (G) Early and Late in Flight

Participant ID	Motion Sickness Susceptibility Score	Step Gain			Change in Step Gain Relative to 1G, SS Baseline		Change in Reduction of Step Gain Early Vs. Late	
		SS, 1G	SS, 0G	SS, 1.8G	SS, 0G	SS, 1.8G	SS, 0G	SS, 1.8G
1	0.0	.265	.258	.192	−.007	−.073	−.013	+.024
2	0.6	.430	.420	.553	−.010	.123	−.011	−.022
3	1.0	.255	.313	.322	.058	.067	−.008	−.058
4	2.7	.593	.666	.542	.073	−.051	+.039	−.043
5	6.8	.332	.328	.305	−.004	−.027	+.023	−.031
6	9.9	.430	.358	.395	−.072	−.035		
7	11.8	.738	.774	.786	.036	.048		
8	12.9	.500	.531	.463	.031	−.037		
9	13.0	.395	.361	.480	−.034	.085		
10	15.3	.234	.202	.217	−.032	−.017		
11	19.6	.540	.560	.528	.020	−.012	−.068	+.024
12	20.1	.468	.315	.362	−.153	−.106		
13	22.4	.293	.283	.272	−.010	−.021		
14	25.5	.351	.406	.362	.055	.011		
15	27.9	.398	.443	.466	.045	.068		
$\bar{X}$		.415	.414	.417	.001	.002	−.006	−.018
SD		.138	.158	.153	.058	.064	.037	.034

sudden stops in the different background force levels. In comparing the step gain across individuals as a function of background force level no significant differences were observed. This means that the peripheral end organs, the semicircular canals, were not affected by variations in force level. The gain averaged .415 and ranged from .234 to .738, and had a high test-retest correlation (r = .8911, p < .001). There was no significant rank correlation between step gain and motion sickness susceptibility (*rho* = .0393).

The time constants of slow phase velocity decay for sudden stops without head movements ranged from 11.7 to 26.4 with an average of 16.6 s (Table 3) and also had a high test-retest reliability (r = .8444, p < .001). The time constants were not significantly correlated with step gain and showed a non-significant rank correlation (*rho* = .4964, p = .08) with motion sickness susceptibility (Figure 3A). Relative to the 1G baseline values, the vestibular-ocular reflex time constants decreased both in 0G and 1.8G, t = 8.65, p < .0001, and t = 3.76, p < .0005, respectively. These decreases were highly correlated with each other (r = .6706, p < .01) but neither was correlated with susceptibility to motion sickness (Figure 3B).

Ten individuals had also participated in sudden stops followed by head movements. The baseline, 1G, no head movement trials had an average time constant of 16.7 s. This value was reduced to 11.3 s when head movements were made in

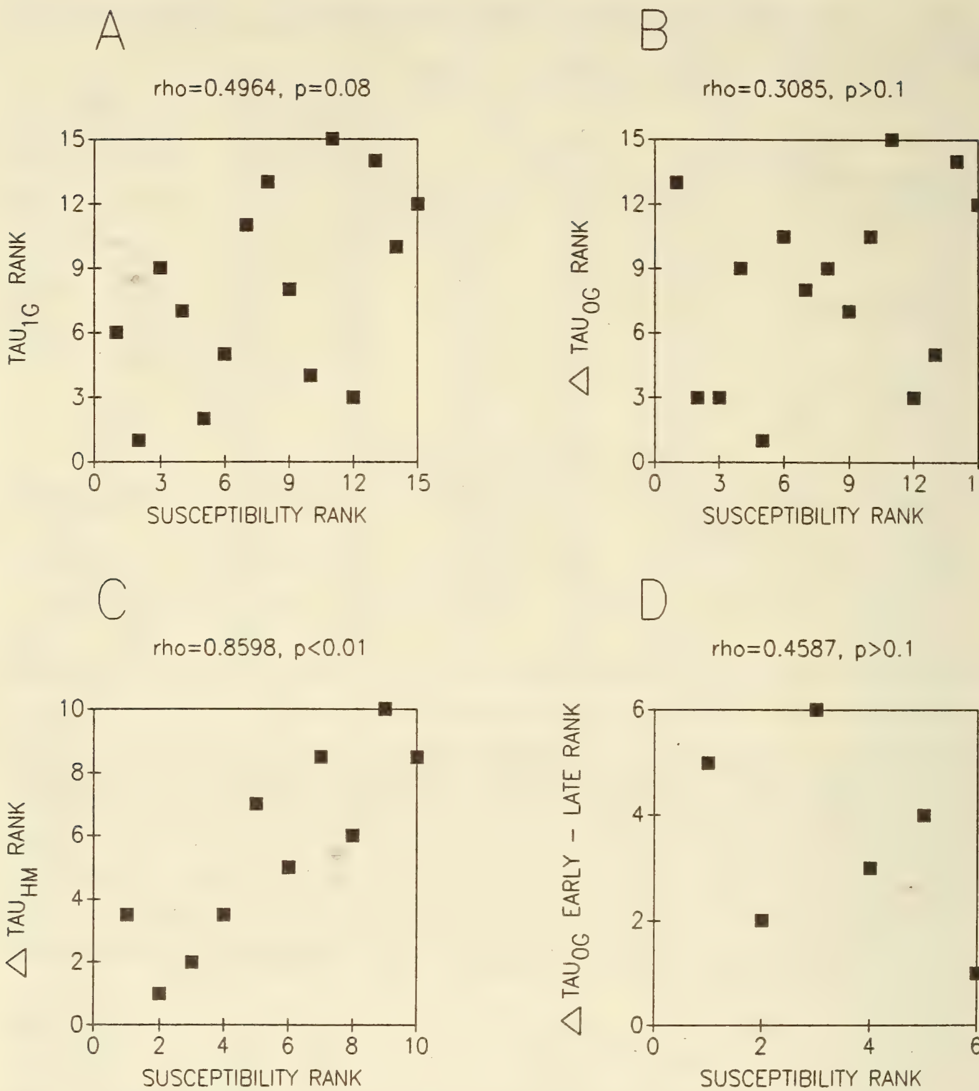

Fig. 3. Graphs of motion sickness susceptibility rankings (lower rank means lower susceptibility) during head movements in parabolic flight versus rankings based on various vestibular tests: A. Rankings of the dominant time constant of slow phase velocity decay following sudden stops in 1G with the head kept still (lower TAU_{1G} rank = shorter time constant). B. Rankings of the reduction in dominant time constant in 0G relative to 1G with no head movements (lower Δ TAU_{0G} rank = smaller reduction). C. Rankings based on reduction in time constant due to post-rotary head movements in 1G (lower Δ TAU_{HM} rank = smaller reduction). D. Rankings of the difference, early versus late in flight, in the reduction of the time constant in 0G relative to 1G (Δ TAU_{0G} EARLY-LATE; lower rank = smaller difference).

1G (Table 3). The decreases in time constants for individuals and their motion sickness susceptibilities (Figure 3C) were positively rank correlated (*rho* = .8598, $p < .01$).

For those six participants who were tested repeatedly during a flight there was

Table 3.—Motion Sickness Susceptibility in Parabolic Flight, Time Constant (s) of Decay of Nystagmic Slow Phase Velocity Following Sudden Stop Stimulation (SS), and Modification of the Time Constant by Head Movements (HM) and by Gravitoinertial Force Level (G) Early and Late in Flight

	Motion	Time Constant				Change in Time Constant Relative to SS, 1G Baseline			Change in Reduction of Time Constant Early Vs. Late	
Participant ID	Sickness Susceptibility Score	SS, 1G	SS + HM, 1G	SS, 0G	SS, 1.8G	SS + HM, 1G	SS, 0G	SS, 1.8G	SS, 0G	SS, 1.8G
1	0.0	15.7	12.2	7.6	13.6	−3.5	−8.1	−2.1	−1.3	+0.7
2	0.6	11.7	9.1	8.5	8.5	−2.6	−3.2	−3.2	0.0	−3.5
3	1.0	16.7	13.6	13.5	13.7	−3.1	−3.2	−3.0	−1.8	−1.2
4	2.7	16.0		10.1	10.5		−5.9	−5.5	+0.2	+0.4
5	6.8	12.0	8.5	10.3	11.7	−3.5	−1.7	−0.3	−1.2	0.0
6	9.9	14.7	8.4	8.4	13.3	−6.3	−6.3	−1.4		
7	11.8	17.4	12.1	12.8	15.8	−5.3	−4.6	−1.6		
8	12.9	19.1	12.4	15.4	20.9	−6.7	−3.7	+1.8		
9	13.0	16.3	10.5	12.0	15.3	−5.8	−4.3	−1.0		
10	15.3	13.7		7.4	12.2		−6.3	−1.5		
11	19.6	26.4	15.6	16.2	17.9	−10.8	−10.2	−8.5	+0.4	+0.3
12	20.1	12.7		9.5	10.3		−3.2	−2.4		
13	22.4	21.1		17.6	20.3		−3.5	−0.8		
14	25.5	17.1	10.4	8.9	11.3	−6.7	−8.2	−5.8		
15	27.9	18.6		12.1	15.9		−6.5	−2.7		
$\bar{X}$		16.6	11.3	11.4	14.1	−5.4	−5.3	−2.5	−0.6	−0.6
SD		3.79	2.33	3.22	3.62	2.44	2.35	2.51	0.93	1.59

a general habituation of time constants. For example, the 1G values decreased from 16.1 to 13.3 s from the beginning to the end of a flight, however, the G force influence remained. In 0G, early in flight, the average reduction relative to 1G was 4.1 s, later in flight it was 3.5 s, a non-significant change; for 1.8G trials the average reductions were 2.0 s early and 1.4 s late, also a non-significant difference. Motion sickness susceptibility was not rank correlated with the early versus late changes in the effect of G level on time constants (Figure 3D). A similar habituation of step gain was also seen (Tables 2 and 3). The 1G values ranged from .481 early to .406 late, but there were no significant mean changes in the 0G and 1.8G gains early or late relative to the early and late 1G gains. Motion sickness ranking was also not correlated with G related gain changes, early versus late in the flight.

Discussion

Over the years there have been many attempts to correlate the gain of the vestibulo-ocular reflex or the time constant of slow phase velocity decay with

susceptibility to motion sickness (deWit, 1954; Bles, deJong, and Oosterveld, 1984). In general, the results have been disappointing because of low correlations or because of limited replicability. The results of the present study insofar as they use like measures are quite similar. For example, we did not find the step gain of the vestibulo-ocular reflex to be correlated with susceptibility to motion sickness, regardless whether step gain was assessed in 1G, 0G, or 1.8G. The aforementioned studies failed to find a relationship between sea sickness and step gain of the 1G, vestibulo-ocular reflex. We interpret our findings of a lack of G-related differences in step gain and a lack of correlation step gain with susceptibility to mean that (1) there was no general response decline caused by the participants' states of motion sickness and (2) that individual differences in peripheral vestibular function (within the "normal range") are not predictive of motion sickness susceptibility in parabolic flight.

Earlier studies have also failed to find a relationship between time constants of nystagmus decay and susceptibility, for sudden stops in 1G. In the present study, we have found a positive correlation of .49 between the rank orderings of time constants for sudden stops and motion sickness susceptibility. Additionally there was a trend for longer time constants and increased susceptibility to be associated. Here it should be noted that earlier studies may have obscured a possible relationship by comparing average values for "susceptibles" and "nonsusceptibles," rather than taking advantage of individual variability on the different parameters. Interestingly, our correlation was achieved using a much smaller set of individuals than many of the earlier studies.

The most robust correlation that we observed was the close correlation between the amount of dumping elicited by head movements in 1G and susceptibility: a positive correlation at the $p = .01$ significance level, with a sample of only ten individuals. This observation is extremely interesting because coupled with the positive correlation between duration of time constants for sudden stops and susceptibilities, it suggests that the greater the velocity storage and the greater the amount of dumping elicited by head movements in 1G, the greater the susceptibility to motion sickness in parabolic flight. And, it may be, that these correlations will hold for other provocative situations as well.

We know for example that many other situations on Earth which involve dumping are extremely provocative. For example, off-vertical rotation and barbeque spit rotation both involve modulation of velocity storage and are highly provocative. A stable visual input can also suppress velocity storage or dump velocity storage that already may have developed. For example, in the sudden stop vestibulo-visual interaction test (Graybiel & Lackner, 1980) participants are exposed to repeated decelerations from constant velocity. The first part of the test is conducted with the eyes closed (the first 20 stops), the next parts with

the eyes open. The eyes-closed portion of the tests would involve velocity storage and is relatively unprovocative for most individuals; however, the parts with full vision to suppress and dump velocity storage are highly provocative.

The present observations may also be useful in understanding other situations in which motion sickness develops. For example, if head movements are made during rotation in a slow rotation room, there will be cross-coupled stimulation of the semicircular canals (one set of semicircular canals will gain angular momentum and another set will lose it as the head is tilted with respect to the plane of rotation). Such head movements are more provocative if full vision is allowed compared with being blindfolded. This visual input would suppress velocity storage. It should now be possible to see whether an individual's susceptibility in different test situations correlates with the degree of dumping he or she exhibits in that situation. If so, it would provide for the first time a purposeful way to look at susceptibility differences across test situations and relate them to the activity of known physiological mechanisms that can be behaviorally assessed.

We raised the point earlier that people can get motion sick in situations where velocity storage does not occur or is not dumped. We would not expect the measures of an individual's capacity for velocity storage and sensitivity to dumping to predict motion sickness in such situations. By extension, we would not expect an individual's susceptibility in a situation where charging and dumping of velocity storage are prevalent to be correlated with susceptibility in a situation where they were not evoked. For example, susceptibility during post-rotary head tilts where velocity storage is first charged and then dumped would not predict susceptibility during vertical oscillation where neither velocity storage nor dumping are evoked. Vertical oscillation is a major component of the stimulus for sea sickness.

These considerations are consistent with our view that patterns of individual differences in susceptibility to motion sickness across situations will only be comprehensible when we (1) understand basic spatial orientation mechanisms, (2) can measure how individuals differ in the operation of such mechanisms, and (3) can discriminate which control mechanisms are etiologically relevant in particular provocative situations.

An important aspect of future experiments concerning vestibulo-ocular adaptation to head movements during rotation will be to look at changes in the vestibulo-ocular response to cross-coupling stimulation, to impulsive decelerations, and to impulsive decelerations followed by head movements to produce dumping. The pattern of variation in these situations should provide insight into factors that elicit motion sickness, changes associated with adaptation of vestibulo-ocular and motion sickness responses, and factors that determine whether adaptation will transfer from one test situation to another.

Acknowledgement

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Individual Differences in Air Traffic Control Specialist Training Performance

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ABSTRACT

This presentation provides an historical perspective of the Federal Aviation Administration's (FAA) investigations into the role of individual differences in predicting performance in FAA Air Traffic Control Specialist (ATCS) training programs. Most of the research in this area has been done to identify tests that could be used to select air traffic controllers.

Introduction

Before discussing ATCS selection procedures, it is necessary to briefly describe the job of the air traffic controller. There are three types of air traffic controllers. En route controllers work at one of about 22 Air Route Traffic Control Centers (ARTCCs) in the United States. Their primary duty is to control traffic moving between airports, although some may clear or approve traffic to take off or land at uncontrolled airports (those not manned by other controllers). En route controllers work high altitude sectors in which the aircraft are moving at high altitudes and at high speeds, or low altitude sectors, where aircraft are beginning to converge on an airport, and are in the process of beginning to slow down and move closer together.

Terminal controllers control traffic during arrivals and departures from specific airports. Controllers in the tower cab environment control aircraft as they move on the ground and as they take off or land; their control extends to about a 5-mile radius of the airport. Terminal radar controllers, or "approach controllers," control the traffic within about 5 and 40 miles of the airport, providing coverage between the en route and tower cab controller. In the United States, there are some four hundred terminal facilities, both tower cabs and radar approach facilities. Within those categories of facilities there are different facility levels, indicating different numbers and types of aircraft controlled and there are

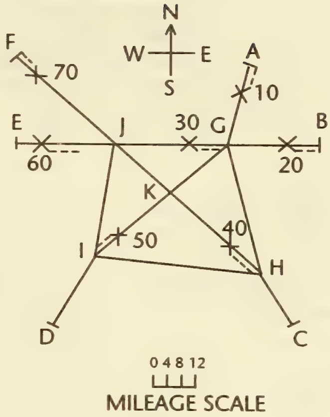
also a few other distinctions between types of facilities that provide different services to aircraft.

Flight Service Station (FSS) controllers file flight plans (primarily for general aviation pilots), interpret weather information so they can brief pilots on weather conditions, and provide services to orient lost aircraft. Because FSS controllers do not formulate clearances to separate aircraft, they are usually considered independently from the other controllers with regard to part of the selection process and with regard to their career progression.

The question with regard to the en route and terminal controllers is whether they perform different jobs. All controllers formulate clearances to ensure aircraft separation; all communicate with pilots and coordinate activities with other controllers. On the other hand, their job functions differ because: 1) the aircraft they control are moving at different speeds and are in different stages of converging on an airport; 2) they may control different numbers of aircraft; and 3) they may or may not use radar as a tool. Radar allows the controller to have a two-dimensional representation of a part of the airspace as a cue for what is going on in the three-dimensional real world. Most en route controllers use radar unless they work in areas where radar coverage is not available (e.g., over the ocean). Terminal approach controllers use radar (but employ different equipment than the center controller) to sequence aircraft into the vicinity of an airport. Tower cab controllers at only the largest facilities have a small radar scope called BRITE to aid in identifying positions of aircraft. However, these controllers do not use the radar to ensure that separation is maintained between aircraft; they also do not receive radar training. Other tower cab controllers do not have access to radar at all. In the absence of radar (which happens only infrequently), controllers use nonradar procedures, which means they keep track of an aircraft's movement through their airspace without a visual representation. They are aided in keeping track of this information by paper flight progress strips on which they indicate the aircraft's flight plan and times when the aircraft is expected to be at a certain location. Tower cab controllers may sometimes make notes on a pad of paper about aircraft being controlled and what they have been approved/cleared to do.

Clearly, air traffic control is a very complex job environment. Before 1964, the only selection criterion for an ATCS was having prior military experience performing the job of air traffic controller. Research had been conducted since the 1940s to identify tests to select controllers, but most of the tests used initially were job samples specifically developed to measure skills used on the job. Such tests as memory for flight information, coding flight data, receiving oral messages, coordinating clearances, devising clearances, and issuing oral communications were developed as predictors, not as criteria. The development of job

AIRCRAFT	ALTITUDE	SPEED	ROUTE
10	7000	480	AGKHC
20	7000	480	BGJE
30	7000	240	AGJE
40	6500	240	CHKJF
50	6500	240	DIKGB
60	8000	480	DIKJE
70	8000	480	FJKID



SAMPLE QUESTION

WHICH AIRCRAFT WILL CONFLICT?

A. 60 AND 70
B. 40 AND 70
C. 20 AND 30
D. NONE OF THESE

Fig. 1. Multiplex controller aptitude test (MCAT) item.

sample tests continued—the first Civil Service Commission (CSC) battery contained a test called Air Traffic Problems. The current Office of Personnel Management (OPM) selection battery implemented in 1981 contains a test called the Multiplex Controller Aptitude test (MCAT); an example problem is shown in Figure 1. While these tests may be predictive of performance, it is not clear from looking at the test what they really measure--the MCAT clearly does not measure a single aptitude construct.

Studies on Performance Prediction

Harris (1987) administered a set of marker tests to Academy entrants to examine their relationship to the MCAT; the MCAT had high correlations with marker tests that measure Integrative Processes, General Reasoning, Spatial Orientation, Logical Reasoning and Spatial Scanning. Low correlations were found between MCAT and verbal comprehension.

These findings are consistent with findings from other studies conducted throughout the 1960s. During the 1960s a number of aptitude and temperament tests were administered to a group of controller trainees, and studies were conducted to follow up on their performance for several years afterward (Brokaw, 1984). The tests administered included eight tests of computational and arithmetic reasoning, six tests of perceptual and abstract reasoning, 4 verbal tests, two tests of perceptual speed and accuracy and four temperament tests. The tests

Table 1.—Biographical Data as Predictors

• High school grades (math, physical sciences)	+
• Self report—likelihood of remaining in FAA ATC work	+
• Self ratings of future performance	+
• Number of times aptitude battery taken	−
• Prior ATC experience	+
• Age at Academy entry	−

used were from the Differential Aptitude Test (DAT), California Test of Mental Maturity, Air Force tests, and California Test Bureau temperament tests. The temperament tests had virtually no relationship with the criteria measures and verbal tests had correlations below .2. Of the other tests, those contributing most to prediction of criterion measure were Air Traffic Problems, Arithmetic Reasoning, Symbolic Reasoning, Code Translation and prior experience.

Just as Arithmetic Reasoning and Abstract Reasoning have consistently been found to be predictors of performance in ATC training, so has prior ATC experience. While not sufficient to use as the sole selection criterion, prior experience contributes to the prediction of performance. In more recent years, it has been determined that control of air traffic using IFR (Instrument Flight Rules) procedures is significantly related to performance at the Academy, but prior control of air traffic using VFR (Visual Flight Rules) procedures is not (VanDeventer and Baxter, 1984). For a number of years, even after implementation of the initial aptitude battery, simply having had prior ATC experience qualified an applicant for extra credit points to be added to the rating based on their OPM test scores; now applicants can only gain extra credit points if they demonstrate job knowledge via a paper and pencil test of occupational knowledge.

Other biographical factors have also been found predictive of training performance (Table 1). A biographical questionnaire is administered to Academy students during their orientation period (first 3 days of class). It has been found in a number of studies looking at thousands of students who entered the Academy between 1980 and 1987 (e.g., Collins, Manning, and Taylor, 1984; Collins, Nye, and Manning, 1990) that prior ATC IFR experience, grades in high school math courses, and self-reports of both expectations of future performance and likelihood of remaining in ATC work are positively correlated with training success, while the number of repetitions of the aptitude battery and age at entry are negatively correlated.

The age factor is especially interesting (Table 2). Cobb and Nelson (1974) looked at the same group of trainees at two different points in their career—at completion of Academy training, and at completion of field training. Age was negatively correlated with attrition in both early and later training. This finding was substantiated by later studies; older students have consistently been found

Table 2.—Age as a Predictor of Attrition

1. 1969 Academy entrants (Cobb & Nelson, 1974)

Age	% Academy Attrition	% Field Attrition	% Retention after 4 yrs	N
≤30	15.1	18.9	66.0	1684
>30	35.5	24.7	39.8	665

2. Subsequent studies of Academy attrition (Kegg, 1988; VanDeventer, 1984)

% Attrition from Academy

Age	1977–82 Entrants	Age	1982–88 Entrants
≤24	26%	≤24	34%
25–30	39%	25–29	45%
>30	48%	≥30	53%

3. Field training attrition for 1981–85 Academy graduates (Manning, 1988)

% Attrition from field training

Age	En route	Terminal
≤25	28%	13%
26–29	40%	16%
≥30	52%	26%

more likely than younger students to attrite (fail or withdraw) from Academy training and from later field training as well, in spite of the requirement limiting the maximum entry age to 30 for new hires.

A number of tests and biographical factors have been identified that have been found consistently over the years to be predictive of success in training. What has not yet been discussed is the criteria measures used in these studies. In the early studies of the 1950s, the criteria were usually "lecture grades and instructor ratings" (Brokaw, 1984); follow up studies used supervisor ratings as criteria. Studies conducted during the 1960s used instructor and supervisor ratings, course grade composites, as well as attrition, career progression, and disciplinary actions. In these studies supervisor ratings were considered the "real" measures of job performance and the other criteria used were evaluated on how effectively they predicted the supervisor ratings.

More measures that might be used as criteria have become available in recent years. Some of these measures might be obtained from the Academy nonradar screen program. The Academy screening program has not yet been addressed during this presentation. In one sense the Academy screen is a training program. Students spend 5 weeks learning aviation and ATC concepts and 4 additional weeks being tested on their ability to apply those concepts in a set of simulated

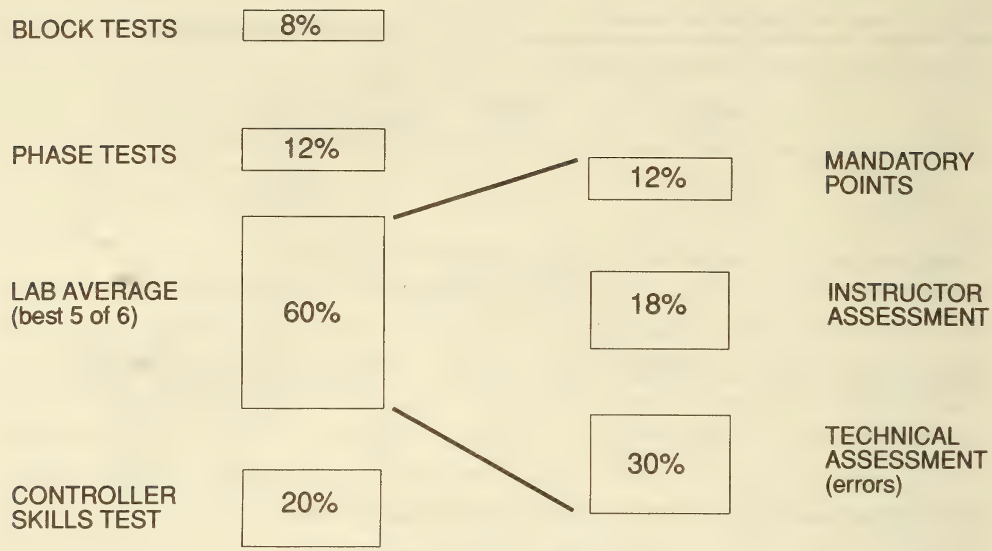


Fig. 2. Nonradar phase weighting system.

laboratory problems which comprise 60% of the final grade (see Manning, Kegg, and Collins, 1989, and Della Rocco, Manning, and Wing, 1990, for details). The Civil Aeromedical Institute obtains all test (and item) scores and the laboratory scores as well as an indication of the number of errors made in various categories on each laboratory problem. However, there is a problem involved in using these scores as criteria measures, although they are commonly used because of convenience. First, the Academy program is a selection procedure; if candidates don't pass, they are fired. The implication of that is that the program occurs at the beginning of a student's career and thus does not measure how well students perform on the job. In fact, the correlation between the score in the Screen and status in later training (corrected for restriction in range but not for attenuation) is only about .44 (Manning, Della Rocco, and Bryant, 1989). Furthermore, the Screen measures performance on the laboratory problems under timed conditions; it is clear that not all candidates have learned to perform the problems when they are tested; thus, we are not measuring asymptotic performance, but are instead measuring performance that occurs somewhere on the learning curve.

Second, the laboratory problems are graded by instructors who are former air traffic controllers. It can be seen in Figure 2, the lab grade is comprised of a technical assessment (TA; based on the number of various types of errors made) and an instructor assessment (IA), which is another subjective instructor rating. The IA suffers from the same problems encountered with most subjective rating systems. Furthermore, the TA score contains error as well; technical grading is

done by instructor counts of the number of errors made. Despite institutional procedures designed to standardize instructor grading, it is not possible to ensure that observation of performance occurring under varying conditions is conducted in a standardized fashion. In fact, the TA and IA are correlated with each other in the range of .8 to .9, and the IA has a slightly higher correlation than the TA with field training status. However, it is not clear what contributes to the measurement of the criterion.

Third, the laboratory problems in the Screen are based on nonradar scenarios, not radar. Nonradar control problems have been found to predict retention in later field training that is based on radar principles, but the screen and field training do not involve the same job tasks. The rationale for using a nonradar-based program for the screen is that if the student can control traffic using nonradar, they'll be able to use radar; that is, if they can keep the information straight in their head without radar, then they can surely do it if they have a two-dimensional cue to help them. However, you can easily find controllers who knew someone who wasn't successful in radar training after passing non-radar, but that hypothesis has never been empirically tested.

While using performance on nonradar ATC problems may be an appropriate predictor of future performance, using such measures as criteria representing job performance is probably not at all appropriate, for the reasons described above. However, if the Screen is considered an inappropriate criterion, what other measures are available to use as appropriate criteria? Several measures of performance in laboratory simulation and on-the-job training are available. Information is collected for every controller trainee regarding every phase of field training they complete. This includes the dates they took the course, the number of OJT (on-the-job training) hours required, the grade, and a rating of their performance as compared with the performance of all others previously rated made by an instructor or supervisor or other person knowledgeable of the student's performance.

The measures of field training performance have a variety of problems which limit their utility as criteria. The available information isn't detailed enough to describe specific strengths and weaknesses in training performance. Furthermore, much of the information may be contaminated. For example, elapsed time by training may be affected by operational policy because the trainee may have to work on a sector on which he or she has been certified instead of training on a new sector (a sector is a piece of airspace for which the controller is responsible; training occurs on one sector at a time). The complexity (the number and types of aircraft and their configurations in the airspace) of individual sectors differs in relation to each other, and students are not assigned to sectors in any particular order (e.g., they don't always train on the easy one first). Furthermore,

students may have more than one OJT instructor. During an evaluation of facility training in which the author participated, training records showed that one student had 25 OJT instructors on a sector, and another had 9 instructors in one day.

Facility philosophies differ regarding training. Some facilities consider training to be a high priority activity and require all trainees to obtain a certain amount of training per week. Other facilities do not consider training to be as important, and trainees at those facilities may not receive training as often. There are differences between options as well; radar training may occur after nonradar at terminal facilities, while nonradar and radar associate training usually occur before, or at the same time as, radar training in the en route option. Finally, air traffic control is considered to be almost an art or craft rather than a standardized job. Controllers utilize different techniques to control aircraft, and as long as their individual techniques maintain aircraft separation and promote efficiency (and conform to the generally defined operating procedures), the methods or techniques used are left to the discretion of the controller.

Because of the factors described above, it is clear that there is much error included in the measurement of training performance. In spite of the errors of measurement involved, performance in the Screen program still has a correlation (adjusted for restriction in range) of .44 with field training status. On the other hand, it is possible that the correlation between the two measures reflects the degree to which the students get along with their instructors, both at the Academy and when they reach field training.

Summary

Clearly, measurement of individual differences in the performance of air traffic control specialists is complicated by the complexity of the occupation, the resulting complexity that must be incorporated in their training, and a number of factors which introduce error into the measurement of training and occupational performance. Considerable research has been conducted which identifies aptitude and biographical factors which have consistently been found predictive of success in training. However, the message that should be conveyed by this discussion is that we need to be very careful about using performance in the selection/training screen program or measures of performance or success in field training as performance criteria. We must better understand how controllers perform the job, in order to obtain better measures of job performance. When those performance measures have been developed, it will be necessary to review past findings and conduct additional studies to determine to what extent the

predictors of performance identified during years of prior research are still predictive of new performance-based criteria.

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Classification Efficiency and Systems Design

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ABSTRACT

The broad objectives of our investigation were: to provide a description of some major validity findings in selection/classification and to give results of a utility study of the Armed Services Vocational Aptitude Battery (ASVAB); to outline several theoretical and practical controversies involving classification efficiency; and to detail future manpower, personnel and training considerations in systems design.

Introduction

The traditional interest of individual differences measurement researchers has emphasized predictor and criterion measures, as well as predicted job performance and the expression of benefits and costs in utility terms such as productivity gains in dollars. A critical first step in developing a classification-efficient job-matching technology is the adoption of a theoretical framework. Three viable competing theories currently exist to explain predicted performance. An earlier theory, situational specificity, was influential a decade or more ago, but today serves mainly as a strawman, advancing a *g*-based theory as recently represented by validity generalization proponents and others. A second theory, specific aptitude, is derived from the tradition of Thurstone's primary factors. Both theories are directed at incremental predictive validity as affected by the structure of the predictor space. The third theory, differential assignment theory or DAT, has a dual focus: (1) on incremental predictive validity—for single job selection, and; (2) on mean predicted performance (PP) for each job computed after assignment from a common pool—for personnel classification processes. DAT is directed at the structure of the joint predictor-criterion space.

General cognitive ability theory suggests that one general cognitive ability factor underlies all valid specific cognitive abilities. The underlying variable, *g*, causes specific aptitudes to have validity in predicting job performance. If it is

true that there is a single factor (*g*) underlying specific aptitudes, and specific aptitudes do not provide any greater prediction than *g* alone, assuming predictive validity is an adequate index of classification efficiency, then the efficient classification of individuals to jobs based on specific aptitudes, or on general cognitive aptitude, is not a pertinent issue. However, if there are several factors that differentially predict performance in various jobs (even though the specific factor validities do not exceed the validities of *g* for each job), then classification is a relevant issue and DAT can make a contribution to both science and the work place.

Specific aptitude theory on the other hand, suggests that job performance is best predicted by one or more specific aptitudes required by the job, rather than by general cognitive ability. For example, performance as an editor would better predicted by verbal and perceptual speed abilities than by *g*. According to this theory, *g* has only an indirect relation to job performance since it is mediated by specific aptitudes, i.e., results from the correlations among specific aptitudes. This theory strongly contributes to the concept of situational specificity to explain subtle differences in job requirements in different settings.

We propose the third theory, DAT, postulating that several factors differentially predict performance in various jobs, providing a coherent framework for job classification. DAT stresses the existence of real differences among predicted performance measures and emphatically denies that classification efficiency is a function of mean predictive validity alone. Instead DAT proposes that classification efficiency is approximated by the mean intercorrelation among predictive performance measures, the number of jobs to which individuals are assigned, the selection ratio, and mean predicted validity. DAT states that the joint predictor-criterion space is multidimensional and factors other than an unidimensional *g* factor contribute a non-trivial amount of classification efficiency.

The key to success in manning a new system with sufficient numbers of trained personnel is early identification of the manpower requirements. Manpower, personnel and training (MPT) planning is an integral part of the design and acquisition process. The MPT programs of the military services provide methods for systematic analysis throughout the development process and, when applied from the outset, result in the manpower issues being addressed with enough lead time to allow MPT to adequately respond to requirements. A more advanced goal of MPT systems is to interact early in the consideration of design alternatives and evaluate trade-offs between MPT and designs and thus go beyond merely supporting MPT requirements of new systems.

A recently completed National Research Council study was concerned with the next generation of aircraft carriers that will become operational around the year 2040. The sponsors of the study were interested in improving manpower

Table 1.—Needs to Improve Manpower Utilization on Future Aircraft Carriers

Weapons systems are increasingly complex and numerous.
MPT cost to support Navy weapon system is 50% of the total life cycle cost of a system.
Youth population will decrease during the next decade; Improves slightly but will not reach levels of 1970s in the early years of next century.
Youth composition will have large number with academic deficits; Navy now recruits 11% in CAT IV (lowest aptitude ratings).

utilization for the reasons listed in Table 1. Note that the MPT cost to support a system is 50 percent of the total life cycle cost of a system. Also note the decline in the youth population during the next several decades. This indicates that it may be more difficult and expensive to recruit for the military services.

Modern carriers are manned by 6000 personnel; the number of authorized maintenance ratings alone on a carrier is greater than 3000. Thus a focus on the possible reduction in the number of maintenance personnel appears to be a key approach to manpower reduction. Such a reduction would not only permit alternative use of space and considerable monetary savings, but if accompanied by the application of improved selection and classification techniques would also result in large productivity gains. Among the approaches to bring about potential improvements in manpower utilization in maintenance systems is condition-based maintenance. The objective of condition-based maintenance is to identify maintenance tasks by detecting degraded or potentially degraded performance by electronic monitoring, rather than responding to failures with corrective maintenance and scheduling "open and inspect" tasks of preventive maintenance. The implementation of condition-based maintenance requires a new philosophy of systems and equipment designs, repair procedures and maintenance training. In contrast, the approach detailed in this report concerns advanced selection/classification techniques and measuring their utility.

Selection

The Army General Classification Test (AGCT) was quite successful in selecting men for specialist training during World War II, as evidenced by the magnitude of the many hundreds of validity coefficients (r) obtained, a few of which are shown in Table 2 (PRS staff, 1945). Since most of the samples for these studies had been pre-selected on the AGCT or on some highly correlated factor, the obtained relationships were, in general, quite restricted and thus considerably underestimated the operational or true effectiveness of the tests. Also the standard error of r varied greatly as a function of sample size. Validity findings shown in Table 2 strongly contributed to the concept of situational specificity,

Table 2.—Training Validities for the Army General Classification Test (World War II)

Tested Population	N	*r*
ADMINISTRATIVE CLERICAL TRAINEES		
AAF	2947	.40
AAF	123	.44
Armored	119	.35
MAAC	199	.62
OFFICER CANDIDATES		
Infantry	103	.30
Ordnance	190	.41
Signal Corps	213	.36
Tank Destroyers	52	.44
Transportation	314	.38
WAAC	787	.46
Infantry	201	.12
Ordnance	190	.09
Combat Arms (13)	5186	.28

Source: Personnel Research Section (1945).

i.e., validities of the same tests for the same jobs, but in different settings, varied because of subtle differences in job requirements. Note, for example, that the four AGCT validities given for clerical courses ranged from .35 to .62 and that validities for the Officer Candidate courses ranged from .09 to .46, using grades as the criteria. Such results served to reinforce the perception of the need for empirical validation of tests for each new application.

Ghiselli made it his life's work to aggregate selection validity data from the 1920s through the 1960s. He analyzed an enormous amount of validity information, with many of the results looking like the findings shown in Table 2. He classified predictors into 20 different test types and jobs into 21 different job families and reported the grand average validity across all tests and jobs as .39 for training and .22 for job performance (uncorrected for attenuation and range restrictions). Ghiselli (1959) expressed his dismay at the lack of validity generalization: "A confirmed pessimist at best, even I was surprised at the variation in findings concerning a particular test applied to workers on a particular job. We never anticipated them to be worlds apart" (pp. 397–398). Hunter & Hunter (1984) reanalyzed Ghiselli's data, correcting for criterion unreliability and for restriction in range, and reported an increase of *r* to .48 for job performance. Such findings led Guion (1976) to state that the inability to generalize validity findings from one setting to another was the major hurdle separating selection as technology from selection as science.

Charles Mosier (1951) first introduced the concept of validity generalization and later Schmidt and Hunter (1977) developed a procedure for correcting for statistical artifacts to arrive at wider generalizations of validity across jobs and work settings than had been recognized earlier.

Table 3.—Average Training Validities of ASVAB Composites for Four Job Families by Military Service

Military Service	JOB FAMILY				
	M & C	B & C	E & E	HS & T	Total
Army	.49	.45	.49	.50	.48
Air Force	.70	.74	.77	.74	.74
Navy	.50	.49	.53	.53	.51
Marines	.58	.58	.53	.61	.58
Total	.56	.55	.59	.59	.58

Source: Hunter, Crosson, & Friedman (1985). M & C = Mechanical and Crafts; B & C = Business and Clerical; E & E = Electronics and Electrical; HS & T = Health, Social and Technology. Number of jobs = 180; Total N = 103,700.

Table 3 shows the average corrected (for range restriction) validities for four military occupational composites in each service against training success criteria (final course grades) reported by Hunter, Crosson, and Friedman (1985). It should be noted, however, that for the Army validities, skill qualification test scores obtained about a year after administration of the Armed Services Vocational Aptitude Battery (ASVAB) were used rather than training grades. Validities obtained for the Army sample more properly should be considered as job proficiency validities using a job knowledge criterion. The different nature of the criteria and differences in time between ASVAB and criterion testing reduces the interpretability of between-service comparisons. Mean validities were: Army, .48; Air Force, .74; Navy, .51; and Marines, .58. The grand mean, across services and 190 jobs for a sample size of 103,700, was .58. The higher level of Air Force validities against course grades, might be attributed to the more technical content or higher complexity of jobs in that service or to methodological differences in the criteria or to increased criterion reliability (with increased course length).

Hunter et al. (1985) drew a very significant conclusion after analyzing the occupational composite validities for each job family in each service. If different aptitudes best predict different job families, the validity of each occupational composite should be highest for its own associated job family and lower for the other job families. Such a result would be indicative of differential validity. The results, unfortunately, indicated that each occupational composite is almost as valid for other job families as for its own. The conclusion reached, then, is that the ASVAB operational composites provide high predictive validity but little differential validity across job families. To translate differential validity findings into a precise measure of classification efficiency, however, would require a simulation study. The results should not be construed as evidence that the ASVAB as a battery does not possess potential allocation efficiency (PAE) nor

Table 4.—Mean Validities of GATB for Training and Job Proficiency at Five Levels of Job Complexity

Job Complexity (decreasing)	Training Outcomes				Job Proficiency Measures			
	GVN	SPQ	KFM	Multiple *R*	GVN	SPQ	KFM	Multiple *R*
Setting up	.65	.53	.09	.65	.56	.52	.30	.59
Synthesizing/coordinating	.50	.26	.13	.50	.58	.35	.21	.58
Analyzing/compiling computing	.57	.44	.31	.59	.51	.40	.32	.53
Comparing/copying	.54	.53	.40	.59	.40	.35	.43	.50
Feeding/off bearing	—	—	—	—	.23	.24	.48	.50
Weighted Mean	.55	.41	.26	.57	.45	.37	.37	.53

Source: Hunter (1983). Test categories: GVN = General Mental Ability; SPQ = Perceptual Ability; KFM = Psychomotor Skill. Number of jobs = 515. Total N = 39,500.

that full least-square (FLS) test composites of the ASVAB would not demonstrate PAE. Hunter et al. results merely show the inadequacy of the current ASVAB composites.

Table 4 shows the mean validities of the General Aptitude Test Battery (GATB) for training as reported by Hunter (1983). Jobs are clustered into job families on the basis of complexity rather than on task similarity. Hunter's method of ordering job complexity is based on Fine's (1955) functional job analysis dimension scheme for rating people, data and things. Of the 515 validation studies which were accomplished, 90 used criteria of training success and 425 used criteria of job proficiency. The average sample size of the studies was 75. The 515 jobs were considered representative of the entire work force job spectrum. Validities were corrected for range restriction and attenuation. A reliability of .80 was assumed for the training criterion of job knowledge and a reliability .60 was assumed for the job proficiency criterion of ratings.

From Table 4 it can be seen that the validity of cognitive ability (GVN) for job proficiency decreases from .56 to .23 with decreases in job complexity, and conversely, psychomotor ability (KFM) validity increases with decreasing job complexity. Results of cognitive ability for training, however, show a fairly high validity regardless of job complexity, although the validity of .65 for the highest complexity job level was much higher than the validity for the lower job complexity levels, with validities ranging from .50 to .57. Psychomotor ability results for training again show an increase of validity as a function of decreasing job complexity. Hunter (1983) states that the findings for training are consistent with the need for good psychomotor abilities for hands-on training situations.

Table 5.—Project A—Measurement Methods and Performance Dimensions

Measurement Method	Performance Dimension	Overall Performance
• Hands-on Tests (Specific Skills) • Written MOS Tests (Specific Skills) • Supervisor Ratings (Specific Skills)	MOS-Specific Knowledge and Skill	
• Hands-on Tests (Common Skills) • Written Tests (Common Skills)	Basic Soldiering Knowledge and Skill	
• Ratings of Leadership/Effort • Awards and Certificates • Combat Effectiveness	Leadership and Effort	JOB PERFORMANCE
• Ratings of Discipline • Avoiding Article 15 • Being Promoted on Time	Personal Discipline	
• Ratings of Fitness • Physical Readiness	Fitness Appearance	

Source: Wise, Campbell, McHenry, & Hanser (1986). MOS = Military Occupational Specialty.

On the other hand, cognitive ability increases in validity as a predictor of job proficiency as job demands become increasingly complex. Similarly, jobs that have low cognitive demands have a significant psychomotor demand. Of course, there are jobs that are exceptions to this inverse relationship. Taken as a whole, job complexity shows a strong effect on validity.

The complementary patterns of cognitive and psychomotor abilities lend themselves to various ability combinations or multiple correlations. Table 4 shows that the average multiple correlation for a training criterion is .57 as compared to an average of .55 using cognitive ability alone.

Importantly, Table 4 provides a clear indication of differential validity required for classification efficiency. For example, the GVN composite (general mental ability) provides high prediction for high complexity job proficiency criteria and low prediction for low complexity criteria. On the other hand, the KFM composites (psychomotor) has the opposite pattern. This is strong evidence of differential validity and for potential allocation efficiency.

Table 5 summarizes the measurement methods and performance dimensions characterizing the common latent structure across nine different jobs in the Army's Project A, a large-scale longitudinal validation study. The latent structure model which was specified included the five job performance constructs shown in Table 6. A confirmatory analysis showed that the overall model fitted extremely well (Wise, Campbell, McHenry, & Hanser, 1986). The latent performance structure appears to be composed of very distinct performance compo-

Table 6.—Validity of Cognitive, Non-Cognitive, and Combined Predictor Composites—Project A

	Job Performance Criterion Factor				
Predictor	Technical Skill	General Skill	Leadership	Personal Discipline	Physical Fitness
Cognitive composites (K = 11)	.65	.69	.32	.17	.23
Non-cognitive composite (K = 13)	.44	.44	.38	.35	.38
Combined cognitive and non-cognitive composites (K = 24)	.67	.70	.44	.37	.42
Validity gain of combination	.04	.05	.11	.21	.22

Source: McHenry (1987). N = 4039. K = number of measures.

nents, and this suggests that different constructs could be predicted by different types of tests. The pattern of validity gains shown in Table 6 confirms that non-cognitive measures, for example, predict motivationally-based criteria better than they predict specific job proficiency criteria.

However, later analyses indicated little potential for differential validity using any criterion other than the specific job proficiency criterion. For generalization across jobs, within each criterion factor, one equation fitted the data for the other four performance components (Wise, McHenry, and Campbell, 1990).

In Table 6 the impact of considering a composite of 24 cognitive and non-cognitive measures for each of the five job performance criteria is clear. Those results highlight the magnitude of validities obtainable by considering all tests types together. The increments over ASVAB validities for the total combined composite of 24 cognitive and non-cognitive tests range from .04 for Military Occupational Specialty (MOS) Specific Technical Skills to .22 for Military Bearing/Physical Fitness. Of equal interest is the actual level of validities reached against the five job performance criteria factors, with multiple correlations ranging from .17 to .70. It may be inferred that if the five criterion components were combined they would most likely contribute to increased selection efficiency but not to increased classification efficiency.

Classification

Traditionally, in selection and placement, only a single job is involved, and can be accomplished with one or more predictors. The outcome is determined by an individual's position along a single predicted performance continuum. Classification decisions provide the basis for assigning a selected pool of individuals to more than one job. As in selection, these assignments can be made on the

basis of a single predictor continuum adjusted to predict performance by reflecting job validities and/or values. When the predictors are adjusted in such a manner that the mean adjusted predictor scores and the mean criterion scores have the same rank order across jobs, a hierarchical layering effect that makes a positive contribution to the benefits obtainable from classification is evident. A hierarchical layering effect due to either a variation across jobs of the validities of job-specific test composites, or to the value assigned to each job and reflected in predictor score means and/or variances, assures that the assignment process is, at least in part, influenced by hierarchical classification.

Classification that does not capitalize on hierarchical layering effects is referred to as "allocation" (Johnson and Zeidner, 1991). While hierarchical classification can be unidimensional, e.g., based entirely on a single predictor, allocation requires multiple predictors measuring more than one dimension in the joint predictor-criterion space. Validity is determined individually against each job's performance criterion; the set of job criteria should also be multidimensional. Thus a classification battery requires a separate assignment variable (criterion specific composite) for each criterion, if allocation is to be maximized.

Brogden (1959) directly linked measurement of classification efficiency (CE) to mean predicted performance (MPP) and thus to utility. His allocation equation expresses MPP as a function of predictive validity, intercorrelations among the least-square estimates (LSEs) of job performance, and the number of job families. Often this equation is misunderstood, e.g., the intercorrelations in the equation pertain to the full LSEs of job performance and not to the intercorrelations among predictor composites. Also, the equation makes it clear that predictive validity is only one term in the equation and thus classification efficiency can not be adequately described by predictive validity alone.

An example of this misunderstanding is revealed in this remark by Murphy and Davidshofer (1988), "The [ASVAB] composites do not provide information about different sets of aptitudes, and that, in fact, any one of the composites could be substituted for another with little loss of information. For most of its major goals, the military would do just as well with a short test of general intelligence" (p. 208). The quote implies that the intercorrelations of aptitude areas are so high that the use of multiple predictor composites are ineffectual. Research shows that in ASVAB there is a mean r of .95 among LSEs of job performance. But this high value still was capable of producing considerable classification efficiency (Nord and Schmidt, 1991). Additionally, the comment also implies that the predictive validity is the appropriate measure of classification efficiency (CE) and that the current operational composites best reflect the potential for differential validity.

Brogden's (1949) historic equation for estimating costs and benefits of a selec-

Table 7.—Brogden's Cost-Benefit Equation

$$\Delta\bar{U} = N_s r_{xy} SD_y \bar{Z}_{xs} - NC$$

where

$\bar{U}$	=	the total utility gains of a selection program;
N	=	the mean number of years selectees remain on the job;
r_{xy}	=	the correlation between the predictor and job performance in the applicant population (the validity of the predictor);
SD_y	=	the standard deviation of job performance in dollars;
$\bar{Z}_{xs}$	=	the average score of those selected in applicant population predictor standard score; and
C	=	the cost of selection per individual.

tion program as a means of demonstrating that testing can save money is shown in Table 7. How much is saved depends on the predictive efficiency of the selection device, the selection ratio and two important recently applied situational variables—the variance of dollar-valued performance to the organization and costs associated with testing and recruiting.

Despite the availability of Brogden's equation since 1949, utility analysis had not received widespread attention until recent years when practical and rational means of estimating job performance in dollars were developed, such as the global estimates procedure described by Hunter and Schmidt (1983).

Utility of the ASVAB

In fiscal year 1987, 315,000 enlistees entered the All Volunteer Force; and of these, 130,000 or 41 percent were recruited into the Army. The Services rely heavily on aptitude information (ASVAB), since most recruits have little or no work experience. The Services' selection and assignment systems are dependent on an interrelated set of complex factors including policies, goals, recruiting resources, recruiter incentives, formal and informal enlistment standards, the willingness of young people to enlist, and the efficiency of the job assignment system in person-job matching.

Nord and Schmitz (1991) conducted an empirical analysis of productivity gains attributable to simultaneous changes in job entry standards (minimum cutting scores), assignment policies and assignment procedures to provide decisionmakers with realistic information in making rational choices for allocating scarce resources among alternative strategies. Taken together, the need for realism and the need to consider opportunity costs imply that, in order for this utility analysis to be useful, it must be context-specific and credible. A total of thirty-three different policies were analyzed. Eleven different job assignment policies and procedures were first simulated under 1984 enlistment entry stan-

Table 8.—Average Validities of Army Composite Used for Assignment to Job Families

Job Family	Mean Validity 1981[a]	1984[b]	1987[c]	1987[d]
Clerical/Administrative	.53	.49	.60	.59
Combat	.56	.44	.54	.55
Electronic Repair	.59	.45	.72	.65
Field Artillery	.63	.45	.39	.55
General Maintenance	.76	.40	.54	.60
Mechanical Maintenance	.52	.45	.62	.55
Operators/Food	.61	.50	.61	.60
Surveillance/Communication	.55	.47	.55	.55
Skilled Technical	.55	.57	.54	.55

[a] Maier, & Grafton (1981).
[b] McLaughlin, Rossmeissl, Wise, Brandt, & Wang (1984).
[c] McHenry (1987); Eaton (1987).
[d] Zeidner (1987).

dards, then under the assumption that those standards were raised by five standard-score points for all Army jobs, and finally under the assumption of a ten-point across-the-board increment in standards. All thirty-three policies were simulated using a same random sample of 4,280 accessions from the 120,281 Army enlistments in 1984.

The utility analysis relied heavily on the work of previous researchers in this area but extended previous work in several key respects, especially the use of empirically based simulations, rather than theoretically derived values, to estimate gains under alternative policies, and also the incorporation of realistic labor market considerations.

Table 8 shows the average job performance validities for nine occupational clusters of job families (all validities include corrections for range restriction). The aptitude area composites are constructed from tests on the ASVAB. The single composite validities used in the present analysis were obtained by combining the validity results of three previous studies and the number of MOS in each job family included in each study. The resulting *weighted average,* tabled in the last column of Figure 8, fell within the range of previous estimates for each job family and close to the unweighted average for the previous studies. The main effect of this averaging was to dampen large and inconsistent variation in validities across job families. Use of optimal full-least-squares (FLS) prediction equations as the assignment strategy raised MPP .334 of a standard deviation unit over random unit selection, and .143 of a standard deviation unit over the current selection and assignment process. Thus, the FLS equations provided 1.7 times the increment of the current policy over random selection and assignment in predicting MPP. As expected, increasing selectivity, i.e., raising job standards

Table 9.—Gross and Net Values and Predicted Performance Under Different Policies

Job Selection and Classification Policy	Mean Predicted Performance	Gross Value	Net Value
Random Selection and Assign	.000	−352.2	−152.4
Current Select/Random Assign	.189	−21.4	−50.4
Current System	.197	0.0	0.0
EPAS	.221	32.5	56.5
Optimal FLS	.334	228.8	260.0

All values are relative to the CURRENT allocation, under CURRENT selection standards (in millions of dollars per year). Gross present value is estimated value of performance gains without accounting for changes in training and recruiting costs. Net present value is equal to Gross value minus these changes.

by 5 points, increased MPP within each of the sets of policies. The use of a 5-point increase in standards using the FLS assignment policy increases MPP from 0.334 to 0.370 over random selection and assignment.

However, simply to know the impact of a policy on performance is not sufficient. Increasing the job standards involves increasing the applicant pool, which, in turn, increases recruiting costs. Therefore, performance gains are evaluated via a benefit-cost model using utility analysis and an alternative economic analysis based on *opportunity costs.*

Table 9 provides estimates of the *gross value* of mean predicted performance change under different policies, as well as the *net value* under one recruiting cost assumption. The gross values shown are the estimated present values of each policy prior to accounting for recruiting and training costs produced by changes in selection ratios and attrition rates. The net values are estimates produced after changes in training and recruiting costs are accounted for. The gross value of the performance gains produced by the current system is about $350 million annually. However, when the large reduction in recruiting costs that could be realized by moving to a 50 percent high-quality accession pool are taken into account, the annual savings provided by the current system drop to $152 million.

Even under the handicap of predictor score optimization, rather than predicted performance optimization, a computer-based efficient performance allocation system, the Enlisted Personnel and Assignment System (EPAS), provides significant gains over the current system, with estimated net gains under current selection standards of $56 million annually.

The final point to be made with respect to these results is that the potential gains from the use of the FLS predictors are extremely large, yielding estimated net gains of $260 million under current standards, even when current Armed Forces Qualification Test (AFQT) quality goals are enforced. Note that this gain will be over $310 million larger than a current selection system with random

Table 10.—Estimated Cost of Achieving Equivalent Performance by Increasing AFQT CAT I–IIIA Accessions[a]

Job Selection and Classification Policy	Mean Predicted Performance	Required I–IIIA (%)	Avg Cost ($K)	Opportunity Cost ($M)
Random Selection and Assign.	.000	.46	4,649	−295.6
Current Sel/Random Assign.	.189	.58	8,142	−20.0
Current System	.197	.59	8,371	0.0
EPAS	.221	.63	9,195	81.6
Optimal FLS	.334	.78	13,155	573.0

[a] Using the current system.

assignment and $412 million over random selection and assignment (without use of testing).

The most serious limitations of the foregoing net present-value (NPV) method is the centrality of the assumption about the dollar value of a standard deviation in performance. While there is persuasive empirical evidence that 40% of salary is a conservative estimate, this *rule-of-thumb* approach is often perceived as subjective, and therefore unreliable. This problem is exacerbated when the rule is applied to public sector activities where no clear valuation of output is possible. An alternative to the NPV approach that, in some circumstances, may provide more useful information for the decisionmaker, is to focus attention on the cost of obtaining a given level of performance using existing procedures instead of attempting to directly measure the net value of the gains achieved under different procedures, i.e., to focus on opportunity cost of retaining the existing system. Using an opportunity-cost approach in this context we ask, "What would it cost to achieve the levels of performance produced under each evaluated policy if the mechanism used to achieve these gains was to simply increase the number of high quality recruits and assign them using the current system?"

Table 10 shows the opportunity costs. In general, the opportunity cost estimates parallel those arrived at under the NPV method in terms of relative magnitude, but are considerably higher in absolute magnitude. The estimated cost of achieving the performance gains provided by EPAS under current selection standards through the recruitment of additional mental categories I-IIIA soldiers is $81 million, compared with the NPV estimated gains of $56.5 million. (Mental category I is the highest category and category IV is the lowest acceptable level for entry into the service.) The increased cost of using the current system, combined with the recruiting of higher quality recruits to achieve the performance provided by the optimal FLS option under current standards, would exceed $570 million.

On the basis of our utility analysis we can suggest changes in military operational classification systems that are based solely on our simulation results. The changes depend entirely on better utilization of information contained in the present ASVAB. Only technical changes in assignment policy and procedures are needed to obtain the productivity gains estimated. Specifically, we suggest the use of: (1) mean predicted performance, i.e., FLS composites, as the objective function for the assignment algorithm, rather than aptitude area composite scores; (2) the FLS prediction equations as the assignment variables rather than equally weighted and reduced numbers of tests comprising aptitude area composites; and (3) an efficient optimal allocation algorithm. The assumption is made that the preponderance of recruits could be persuaded to accept the jobs in which they can perform best.

Effective Selection and Assignment in the Development of New Systems

Emphasis needs to be placed on more effective selection and assignment of personnel in the development of new systems. The first step in this process is the determination of qualitative personnel requirements of each new job in terms of multidimensional measures of predicted performance. We have already progressed almost as far as we can go in the achievement of utility within the constraints of a system which measures quality of input in terms of general cognitive intelligence. The next step is the assessment of personnel resources employing the same measures used to determine requirements. By matching resources and requirements we obtain the constraints that must be applied in the design of a system that makes the optimal use of personnel resources. We contend that an optimal distribution of the applicant population to jobs in such a way as to maximize predicted performance on the job requires multidimensional predictors for selection, classification and assignment. Classification efficiency must be considered in developing the selection and classification batteries, in the determination of sets of job families, and the determination of corresponding test composites for making assignments to jobs.

Capabilities for meeting the manpower quality requirements of a new human-machine system under development can be increased at least three ways. If we can afford the increased recruiting costs we can decrease the selection ratio, that is reject more applicants. Or, we can reduce the complexities of jobs by shredding out each specialty into two or more specialties. These approaches provide means of trading off the required quantity (and cost) of applicants against the quality of personnel that can be placed on the job. Second, design and human-factor engineers can reduce qualitative requirements by simplifying

the tasks of the human component or by improvement of training aids. Third, apply an economical means of increasing quality of assigned personnel through the use of classification-efficient measures for both selection and assignment.

Applied psychologists working in the field of human-machine interface have been heavily concerned with individual differences in the conduct of research and development for new systems. Implementation of MANPRINT in the Army, HARDMAN in the Navy, and IMPACT in the Air Force, assure that MPT components of new systems are not ignored. Many of the aspects of MPT can be improved by the substitution of classification-efficient multidimensional test-batteries.

There are several primary factors for increasing utility, one of which is related to classification efficiency (CE). CE is heavily dependent on the increase of mean predicted performance on the job, i.e., MPP, which can be best realized through increasing classification efficiency in both selection (using multidimensional selection) and classification. The other factors are reduced attrition and recruiting costs, and trade offs between all three.

Utility is closely associated with the value of mean predicted performance on the job in several ways. A higher MPP permits more effective hardware designs, reduces training costs and provides higher skill levels on the job. Skills are retained longer and productivity is generally increased—raising system performance.

Effective selection and classification of personnel to multiple jobs requires the integration of procedures and predictors that are classification efficient. The development of such a personnel system draws upon the skills of operations researchers, management, and computer specialists, as well as measurement psychologists who provide the classification efficient measures. There is also a role for the human factors specialist in assuring that human skills most predictive of total system performance are identified and described to the measurement specialists.

We define our classification efficiency (CE) index as the MPP standard score computed after personnel have been assigned to the job from a common pool. The potential classification efficiency (PCE) index is this same index except that assignment to the job must be accomplished using an optimal assignment procedure in which MPP is maximized and each predicted performance (PP) score is expressed as a least square estimate of the performance criteria for each job. Each PP score is computed using the full classification battery.

When we undertake research relating to the classification efficiency of instruments, test batteries, assignment (test) composites, or sets of job families, we use PCE as the basis for making comparisons across alternative approaches (conditions). In recent years, most measurement specialists have emphasized the im-

Table 11.—Common Erroneous Assumptions in Classification

Use of 3 or 4 tests in an assignment battery provides as much CE as 10 or more tests.
Maximizing SE will maximize CE without special consideration of CE in choosing predictors.
Since predictive validity of unit-weighted composites in cross samples may be superior to LSE weights, LSEs are assumed to be less effective than unit-weighted composites for classification.
A small number of job families and associated test composites used as assignment variables can provide as much CE as a larger number of families.
New predictors for use in classification batteries can be effectively selected solely on the basis of their contributions to predictive validity.

provement of predictive validity in classification situations where PCE would be more appropriate. A number of these specialists in the forefront of the validity generalization movement have concluded that since a single general cognitive ability measure dominates most personnel test batteries, the MPP obtainable from the use of differential test composites in an independent sample can only trivially exceed the MPP obtainable from a single efficient measure of *g*. The validity generalization movement has been highly instrumental in the general rejection of the earlier theory of situational specificity—a theory which held that a tailored test composite is required for predicting performance on each job situation. As noted in the introductory section, we propose a third theory, differential assignment theory (DAT) which accepts many of the tenets of the validity generalization movement without adopting their pessimism regarding the utility obtainable from personnel classification, and emphasizes the importance of measuring classification efficiency by means of either PCE or CE (Johnson and Zeidner, 1991).

Validity generalization proponents often accept some classification assumptions (Table 11) as facts. Belief in these tenets leads to discounting the utility obtainable from personnel classification. We have conducted two model sampling experiments and have four more in progress which clearly prove these assumptions to be erroneous. For example, more PCE is obtained from a battery of 10 *best* tests than from a battery containing 5 *best* tests. More potential classification efficiency can be obtained when test selection indices that measure classification efficiency are used as compared with the use of indices that reflect predictive validity. Also, optimal assignments to 18 jobs provide higher PCE in independent samples than when assignment is made to 9 jobs. Differential assignment theory is based on three major assumptions. The most important of these is the optimistic premise that the joint predictor-criterion space, as commonly encountered, provides a non-trivial degree of multidimensionality and provides a classification efficient structure, i.e., rotatable into simple structure. We have evidence that this can be present even when the first principal component provides 80% of the total factor contributions. The second assumption is

that a utility model making use of MPP as the starting point is appropriate for the measurement of classification efficiency. The third assumption is that the state-of-the-art in computer technology has made it practical to make common use of computationally complex algorithms.

DAT has been used to generate more than 20 principles. The first of these selected principles relates to the contention of some investigators that classification efficiency is automatically maximized under circumstances that maximize selection efficiency. DAT clearly indicates otherwise and we have accumulated considerable simulation results supporting this principle. We also have convincing simulation results that support these principles: (a) more predictors can contribute to maximization of CE as compared to SE; (b) predictive validity does not measure CE; and (c) the equation provided by Brogden (1959), described earlier, is a robust and useful model.

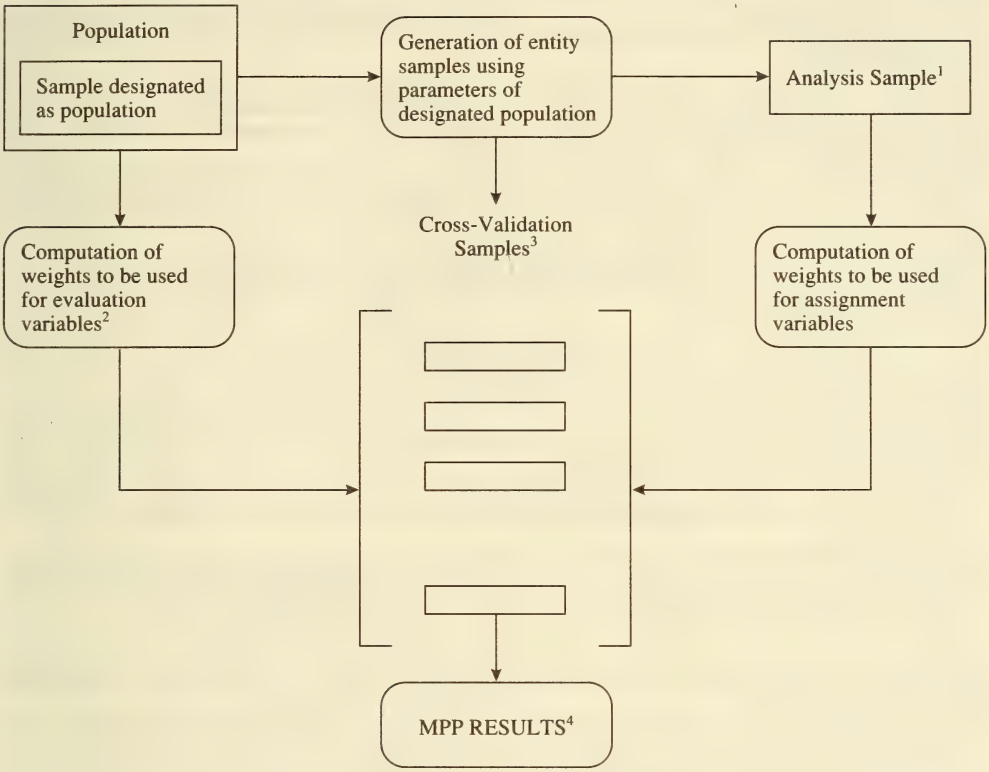
Differential assignment theory requires as a research paradigm the simulation of the classification process in order to compute either CE or PCE. Such a simulation can be based on empirical scores from a data bank or may use synthetic scores generated by a model sampling process. The latter involves generating random normal deviate scores and the transformation of these scores to scores with expected means and covariances equal to those of a designated population. Model sampling provides synthetic scores with the same statistical properties as would be provided by a random sample of empirical scores drawn from a multi-variate normally distributed population.

Model sampling experiments can incorporate safeguards against the presence of sampling and other biases - safeguards that are difficult to provide in simulation experiments based on empirical data. A typical model sampling paradigm is provided in Table 12. It commences, in the upper left hand corner, with a designated population. The parameters of this population are used to generate synthetic scores, thus providing an analysis sample and 20 or more independent cross-validation samples.

Summary

The potential gains for various approaches to improve classification efficiency have been estimated. A study by Sorenson (1965) and the results of on-going model sampling experiments at The George Washington University suggest that the substitute of FLS composites for the existing Army aptitude area composites would provide a 100% gain in an optimal assignment process. Based partly on DAT psychometric predictions, and partly on model sampling results, we believe increasing the number of Army job families from 9 to 20 would provide a

Table 12.—Typical Model Sampling Research



[1] Job validation sample sizes equal to those used in Project A first-term concurrent validation study. [2]Evaluation weights computed from Project A empirical sample designated as the population. [3]Sample size of assigned entities number from 200–300; in the aggregate, N numbers in the thousands for each strategy. [4]Predicted performance is computed using the same evaluation variable and same weights for each job across all experimental conditions.

further gain of 100%. If the differential validity of current predictors was increased, the expected gain in MPP could approximate 100%. The use of appropriate multiple-criterion components common to all job families to varying degrees of importance should provide for the detection of further gains that are not estimated here. The total gains from the implementation of all these improvements should easily exceed several hundred millions of dollars annually and/or greatly increase the quality of personnel performance in the military services.

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Distance Learning in Military Training

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ABSTRACT

Instruction by telecommunications-based distance learning systems connected to remote U.S. military sites has demonstrated that students attain test scores equivalent to those obtained with traditional classroom instruction. Student attitudes toward remote methods of instruction indicate that critical to greater acceptance of those techniques is the enhancement of instructor-student interactions during and after training-sessions. Installation and operational costs for fully interactive, audio-visual instructional systems are high but declining. Costs for less robust systems are lower, and it is estimated that some approaches can be amortized over several months.

Introduction

The duration of a technological generation has been estimated to be about five years (Gopher & Kimchi, 1989), and that brief span demands that more frequent training be provided if the technical currency of the working population is to be maintained. Within some organizations, particularly the military, the maintenance of technical skill-levels in an era of declining force-size has additional value as a force multiplier. Costs for school-house training for the update of technical skills are high, and there is a need to determine the cost-benefits of alternate modes of training, especially for personnel who are distributed over a wide geographic area. This is an especially acute problem for the military where the number of people to be trained, costs, and resource demands are considerable, and there is a requirement to bring training directly to individuals, rather than the reverse. It has been estimated (Fletcher, 1990) that on an average day in FY90, about 208,000 active duty personnel and 47,000 National Guard and Reserve personnel received formal training, at an annual cost of approximately $18.3 billion, and with a resource requirement of 176,000 military and civilian personnel to conduct and support those instructional programs.

There has been a progression in the instructional approaches used by U.S. military training organizations to provide efficient and effective training pro-

grams. Computer-based training is one technique that has met some local needs. A variation of computer-based training made use of video-disc systems (Fletcher, 1990) whereby students interacted with knowledge bases and were aided by computer-based systems which tailored the pace and level of instruction to individual ability and preference. But to serve the training needs of widely dispersed students who require long-term programs, the military has evaluated several telecommunications-based distance learning systems. Future training systems are expected to use artificial intelligence techniques to individualize instruction with interactive remediation and retesting and to assess the learning style of each student (Griffin & Hodgins, 1991).

Distance learning technologies. Distance learning has been described (Wells, 1990) as a teaching approach that has these components: (a) instructor, students, and an implicit contract between them; (b) physical separation between instructor and students, as well as between students and the instructional institution; (c) two-way communication between instructor and students; and (d) use of course materials specifically designed for distance study. Subsumed under that term would be the various methods that are made available for communication between instructor and student, such as teletraining and teleconferencing.

Teleconferencing is a generic, industrial term that incorporates four major forms of telecommunications technology used for transmissions between individuals and groups: video, audio, audiographic, and computer. The capabilities of those four media-forms offer different possibilities for the implementation of instructional strategies:

Video. Television systems are used to deliver training materials and they can be linked to remote sites by satellite, land line, or microwave communication systems. Video teleconferencing may be presented in an interactive, digital form which will allow two-way video and audio messages to be exchanged between instructor and students at each site on the training network. An analog form (usually called business TV) provides one-way video imagery combined with two-way audio interaction between instructor and the training participants; however, the interaction is essentially audio (Chandler & Harris, 1991). Where the element of student-instructor and student-student interaction is deemed essential, interactive video systems have been adopted (Bailey, Sheppe, Hodak, Kruger, & Smith, 1989). On the other hand, analog video has been demonstrated to be adequate within industrial firms, e.g., IBM, Sears, and General Electric, for company-wide meetings directed at information transfer. More than 50 networks and 11,000 reception sites have been developed by industry (Johansen, 1988). In most cases, these systems are used for both business-information purposes and for corporate distance learning.

Audio. Conferencing with audio systems is achieved with an interactive conference call over low-cost commercial telephone lines that connect the instructor with the students. Instructional costs are lower with these systems and they have proven to be adequate where there is no need to transfer video imagery and graphic data.

Audiographic. In these systems the instructor employs a telephone conference call to send timing signals to student computers that key stored, digitized images which become accessible to the students for instructional purposes. Training costs are reduced when the type of instructional program makes it feasible to forward the requisite video materials prior to the instructional session rather than transmitting them during the session.

Computer. Student workstations are linked to the instructor's computer and the students are able to access the instructor's files, download that information to their own computers, and exchange information with the instructor and the other students about the instructional program. Those exchanges may occur in real time between the instructor and fellow students, but in most cases, the communications are asynchronous, i.e., at times preferred by the individual student (Johansen, 1988). Studies within an experimental meeting room (Stefik, Foster, Bobrow, Kahn, Lanning, & Suchman, 1987) have established the feasibility of collaborative work by 2–6 persons via asynchronous communication and discussion. The successful operation of another computer-mediated communication system (Malone, Grant, Tarbak, Brobst, & Cohen, 1987) demonstrated that an intelligent information-sharing system can adequately support problem-solving activities by groups.

Until recently, the term teleconferencing was used to describe any of these four telecommunications media without regard to the purpose of the conference. Now, the term *teletraining* is being adopted to refer to teleconferences specifically directed toward distance learning. Therefore, teletraining may be defined as the use of teleconferencing technology to convey educational and training information to participants who are geographically dispersed.

Training Effectiveness. Distance learning for adults has been fostered by a number of educational institutions with diverse programs (Guthrie-Morse & Julian, 1989; Pugh, Parchman, & Simpson, 1991; Saffo, 1990) which used teletraining for instructional purposes. Training programs that employ teletraining are also widely used by business firms for professional training. Surveys conducted on the policies and experiences with those approaches at a variety of institutions uniformly conclude that its educational/training outcomes are equivalent to traditional residential-training, and find that students have only a slight preference for conventional training methods (Pugh, Parchman, & Simpson, 1991). Despite large investments in these techniques, there has been a

shortfall on formal, controlled studies to determine their compatibility with student expectations and instructor capabilities, functionality in courses of different types, and the match with the cognitive-processing abilities of students (Bailey et al., 1989). Experimental evidence is insufficient for analysts to tease out from case studies on distance learning that which is most relevant to the assessment of the principal questions that have been posed on its effectiveness and utility.

In their recent review of the research literature on human performance, Gopher and Kimchi (1989) identified the display of, and interaction with, complex visual information as major issues. Among the critical questions in communication systems were the methods to represent properly the world one wishes to depict, and the physical attributes of that representation. These questions have led research investigators to theoretical studies of how perceptual events are encoded, and the answers are often sought within the framework of feature-analytic or bottom-up processes (Treisman, 1986), global or top-down processes (Navon, 1977), and the in-between boundary processes (Kinchla & Wolfle, 1979). These notions as well as theories of data-driven and concept-driven processing (Rumelhart, 1977) could provide a rich basis for guidance in the design of training programs that depend on the presentation of complex information. Such guidance is essential for the selection of instructional methods like video-based teletraining and teleconferencing which put strong emphasis on the visual medium (reducing the textual), mute the affective content, and enlarge the cognitive components of instruction. However, those major factors in training effectiveness have not been considered in the design and evaluation of field studies with military distance-learning systems.

Cost factors. Instructional designers have envisioned the development of cost-effective systems wherein students would be trained at locations of convenience yet receive instruction that was comparable in effectiveness to that provided in conventional classroom-settings (U.S. Congress, 1989). Costs for most training systems are expressed in terms of student throughput, i.e., the cost-per-student. Early on, television emerged as a primary medium for instruction and educators exploited the power of that technology for instructional purposes, both directly and with videotapes, for broadcast to distributed locations. To offset the high costs of television studios, satellite bandwidth, and a professional production staff, large numbers of students had to be involved in each television broadcast. As the number of students increased, the opportunities for student-to-teacher and student-to-student interaction decreased. This lack of interaction in those using television techniques was found to be incompatible with a student's need to communicate with the instructor and their fellow students (Pugh,

Parchman, & Simpson, 1991, p. 29). Therefore, while these systems were cost efficient, they were often found not to be training effective.

Operating costs for teletraining systems are fairly easy to quantify. The cost factors include: facilities construction/modification needed to accommodate the technology employed; hardware/software; transmission or telecommunications; maintenance; and personnel for production and support staff. Of the teletraining technologies discussed here, only analog video teleconferencing (Business TV) requires special facilities, although digital video teleconferencing may require some site preparation to accommodate the telecommunications equipment. This technology also requires a dedicated staff to operate equipment at the originating site. The other technologies all require some level of training to operate, but all, including the digital video teletraining, can be operated by an instructor or student as a collateral duty.

The telecommunications costs associated with both types of video teletraining systems remain the most complex issue involved in determining the cost of a teletraining system. There are different transmission media, such as satellite, microwave, and fiber optics; there are private and public networks; and there are dedicated, as well as pay-as-you-go or ad hoc services. Given these variables, it is difficult to give exact costs. Generally speaking, the greater amount of bandwidth used, the higher the cost. Analog television uses the equivalent of a 90 megabits per second digital signal. When that signal is compressed many times its original size, as it is with digital video, to 512 kilobits per second, the cost is lower. However, while an analog broadcast signal may cost more per hour, that cost is constant regardless of the number of sites in the network. If the cost is \$2,000. per hr., it is the same \$2,000, whether it is downlinked to 5 sites or 100 sites. While digital signals may only cost \$200. per hr., that cost is repeated for each site on the network, as each site is both a downlink *and* an uplink. If there are 10 sites in a digital network, the cost is \$200. × 10, or \$2,000. per hr.

The more important components for distance learning are those that control access, provide storage, and manipulate information, such as micro-computers, display devices, optical memories, facsimile machines, and scanners for graphic images. In the future it is anticipated (Simpson, 1990) that multimedia workstations that access computer data-bases will be joined with high-definition television, facsimile, and telephone devices, to create a versatile linkage between student and instructor that will be rich in information, and essential for some training purposes.

The introduction of analog video teletraining systems has been slowed by investment costs. A complete uplink facility with studio and its associated electronics, has been estimated to cost between \$1,000,000–3,000,000. Downlink

sites are less expensive, costing on the average of $6,000.–10,000. Satellite transmission is generally distance insensitive, but its cost varies with the bandwidth that is used: (a) C-band (6 GHz on uplink and 4 GHz for downlinks) costs between $200.–500./hr.; and (b) Ku-band (14 GHz on the uplink and 12 GHz on downlinks) runs between $200.–600./hr. Under development are Ka-band systems (30 GHz uplink and 20 GHz downlinks) that require very small dishes (1 m) for which costs have not yet been determined. A satellite downlink with receiver, transmitter, and dish, costs between $800.–18,000., depending on bandwidth that is used, and the informational features that are required (voice, data, and/or video). When a steerable rather than a fixed dish is employed, the cost is multiplied by about three. Finally, operational and programming costs demand a substantial, long-term financial commitment.

Instructor factor. The attitude of the instructor toward these systems has to be weighed since the teacher is a key element in the success of distance training. Romiszowski (1981) has reflected on the issues that bedevil designers when new techniques are to be introduced for the improvement of instruction, and his analyses have focussed on the level of the instruction, the instructor, and the adequacy of the methods being replaced. He has argued that there is a need for different instructional strategies for the exposition of facts, discovery of principles, development of algorithmic procedures, and generalization to concepts. In his view, at the level of skill development, instructional media should provide an opportunity for a student to practice the behavior to be learned, and to use the appropriate sensory channels for communicating the requisite information. Among the instructor factors, Romiszowski cautions that efforts have to be made to prepare the teacher to accept and use the new medium, to determine the essentials that are to be taught, to reduce demands on the instructor for significant changes in teaching practice, and to allay any fears or negative attitudes that new gadgetry might engender. It is anticipated (U.S. Congress, 1989) that teacher preparation for distance instruction (teletechniques) will require increased attention to: (a) the creation of rapport with students; (b) the encouragement of participation; (c) refinement of presentation style, such as volume and tone of voice; and (d) provisions for regular feedback to the student. Most teachers have mastered these skills in face-to-face instruction to a level of automaticity but for distance learning, they would have to be exercised more consciously and aggressively.

Effectiveness factors. The Office of Technology Assessment (U.S. Congress, 1989) has thoroughly examined the effectiveness of video distance-learning for elementary and secondary-school students, and outlined the technological, economic, institutional, and policy barriers to its further development. The general conclusion was that such methods work with motivated older students and

professionals, however doubts were expressed about their suitability for young and/or academically weak students. All of these considerations need to be assessed carefully before recommendations for adoption of distance-learning approaches are made. Caution has to be exercised in the interpretation of data on the relative effectiveness of distance-learning approaches because there are serious questions on their equivalence to traditional instruction (Wells, 1990). The materials that are developed for remote learning are selected because they are most appropriate for the learning task, the instructor teaches differently, and the array of technology—particularly computer-mediated—exceeds that employed in the conventional teaching situation. The analysis reported here will focus on the experience of military trainers with three forms of distance learning: digital and analog video teletraining, and asynchronous computer teletraining.

Effectiveness and Acceptance of Distance Learning in the Military Environment

Four military distance-training systems, two in the U.S. Navy and another two supported by the U.S. Army, have been identified that serve adult learners and have been the object of evaluative studies. They will be examined for measures of performance effectiveness relative to conventional training and for assessments of student acceptance of that mode of instruction. Military training requirements represent a highly promising area for the employment of distance-learning techniques for a number of reasons. The number of students and variety of courses served by the military training establishment is very large, so that instructional costs are significant. Attendance at training programs involves costs for travel, per diem, learning resources, and time away from regular duties, for both students and instructors. Another important factor that influences training opportunities is the narrow temporal window that is available for training, especially in the case of the Reserve forces.

Navy Fleet Combat Training Center–Atlantic. The digital video teletraining center at NFCTC-Atlantic has been in operation since early 1989 at Dam Neck, VA, and currently links six different sites, each capable of originating and receiving audio-visual signals, along the East Coast, by Ku-band satellite stations. There are two remote sites on Naval installations within the Dam Neck area, and the others are at: Newport, RI; Norfolk, VA; Charleston, SC; and Mayport, FL. The network exchanges compressed, digital, encrypted, two-way video and audio information (Chandler & Lucas, 1989; Pugh, Parchman, & Simpson, 1991), at a transmission rate of 512 kilobits per second. KG-81 encryption devices allow training to be conducted up to the security level of secret. Classrooms are equipped with fixed cameras that are focussed on the instructor,

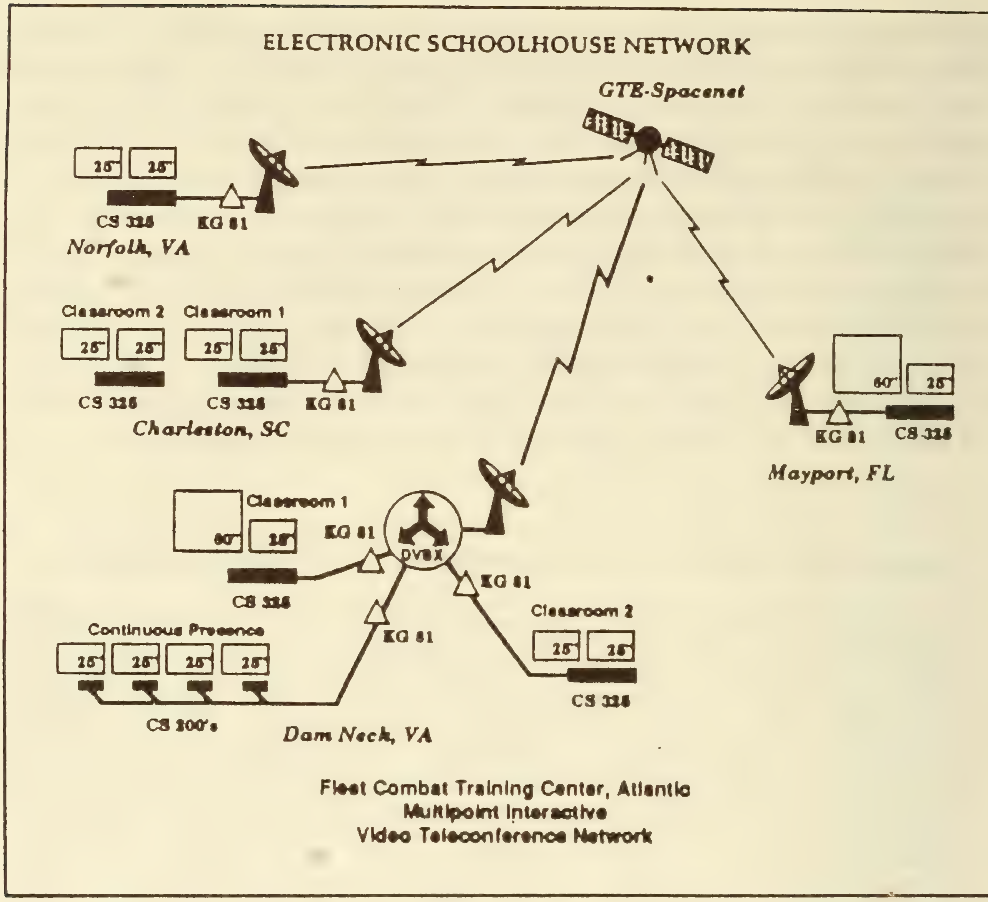

Fig. 1. Teletraining network originating at Naval Fleet Combat Training Center-Atlantic (Chandler & Lucas, 1989).

the students, and downward for graphic presentations; each room also has a small number of sound-activated microphones and the instructor wears a clip-on microphone. Whenever a student at a remote site queries the instructor, all sites on the network are switched by that audio signal to a video of that classroom. The majority of courses delivered with this system are lecture-based and completed within one week.

Formal experiments were conducted with five courses that originated at Dam Neck and transmitted to five of the remote sites (Fig. 1). The courses were concerned with diverse topics such as planning, supervision, gun battery alignment, and ammunition administration. An equal number of students (178) participated in the courses at Dam Neck and at the remote sites (Griffin & Hodgins, 1991). The courses were transmitted over a three-week period. Data collected on student evaluations at the originating and remote sites allowed for a

comparison of the effectiveness and acceptability of this teletraining system with the standard class-room setting to which these students were accustomed (Rupinski & Stoloff, 1990). Results of those assessments showed no significant performance differences in coursework between the students at the originating site and the various remote sites; teletraining was equally effective as residential training in meeting the objectives of all of the courses. No significant differences were reported by the students on: (a) general attitude toward the instructors; however, expressions of disappointment regarding their non-availability to the remote sites after the class sessions did appear; (b) quality of the audio-visual systems was regarded as similar at all locations; (c) tests/homework were not rated as any more burdensome or difficult; and (d) course contents were rated at similar levels. Sizeable differences, however, were noted in the responses of the students at the remote sites with regard to: (a) the degree of interaction with the instructor; it was cited as insufficient by 20% of the students; (b) the number of opportunities to talk and ask questions; this factor troubled 11% of the students; and (c) preference for teletraining vs. residential training methods; 12% of the students opted for the traditional mode of instruction. When invited to suggest improvements for the courses, the students focussed on the technical problems that had occurred in the operation of the equipment, and the decreased level of interaction with the instructor. Bailey et al. (1989) have compiled a set of guidelines, based on experiment, experience, and expert opinion, that provides design solutions for most of the criticisms that have been made of the teletraining approach.

Navy Fleet Combat Training Center–Pacific. During a survey (Simpson, 1990) of current communication systems for delivery of training programs, alternative designs for a distance-learning system were considered and led to the specification of optional systems for use in Navy instructional environments. The most serious training problem to be met by such systems was expected to be the ability to meet the requirements of individuals aboard ships at sea, dockside, and at the 235 Naval Reserve training sites in the continental U.S. One of the distance-learning configurations that was proposed was a teletraining system for group instruction, similar to that in use at the NFCTC-Atlantic. However, for a test system installed at NFCTC-Pacific in San Diego, a land line with a transmission rate of 1.54 megabits per second was employed instead of a satellite to link two Naval sites on the West Coast. As with the East Coast network, digital signals were encoded with a VideoTelcom (VTC) System 300 Codec, and encrypted with KG-81 devices, to provide secure two-way audio and video transmissions (Simpson, Pugh, & Parchman, 1990). Careful attention was given to the design of the originating (Fig. 2) and remote (Fig. 3) classroom facilities which imposed few demands on the instructor. The equipment was operated by

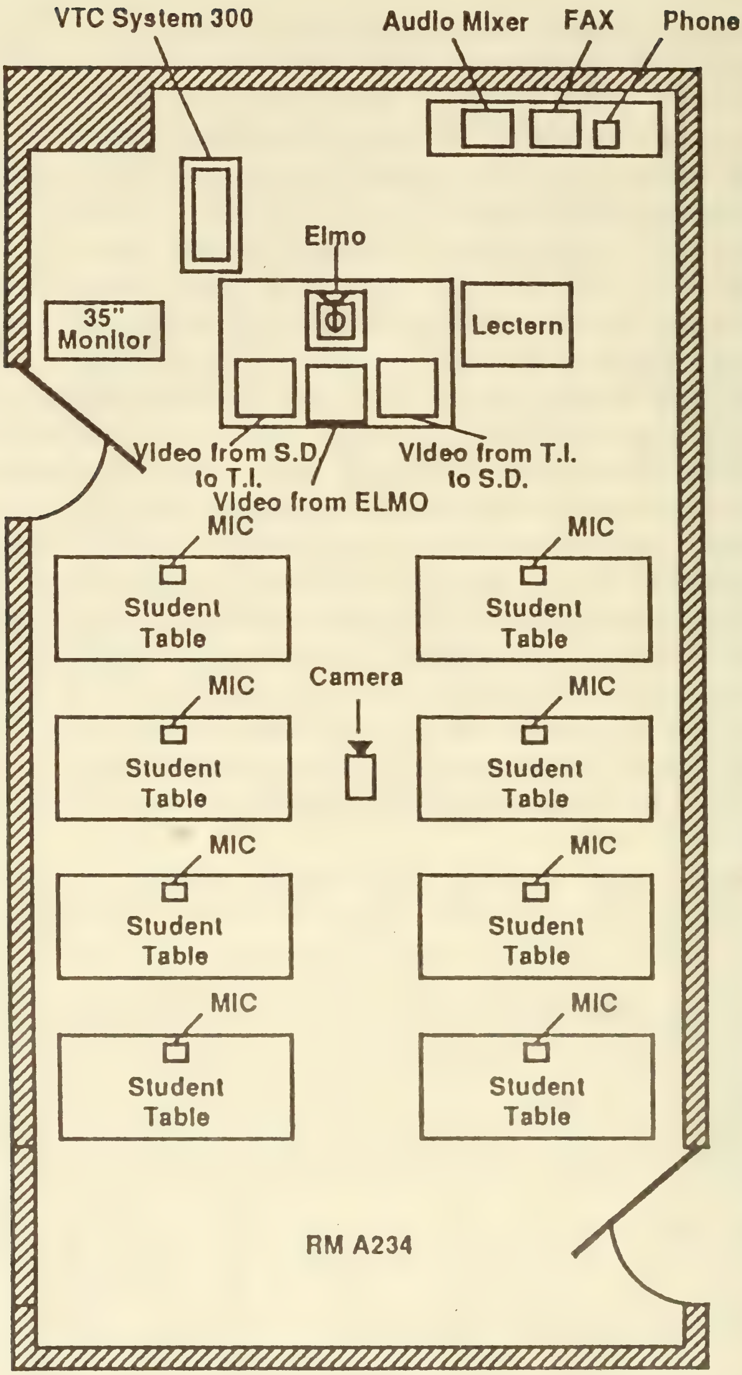

Fig. 2. Equipment configuration of teletraining system originating at Naval Fleet Combat Training Center–Pacific (Simpson, Pugh, & Parchman, 1990).

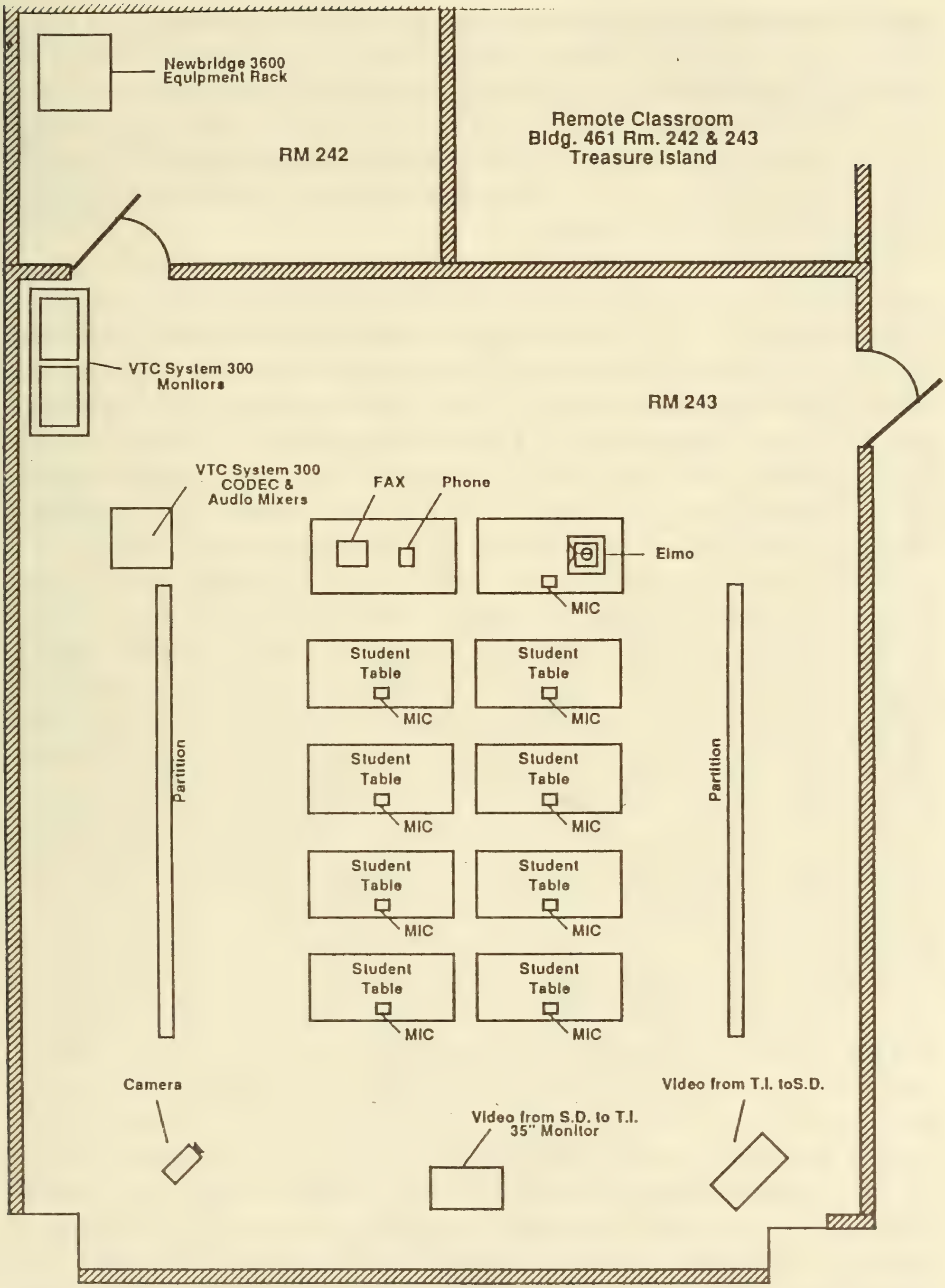

Fig. 3. Equipment configuration of teletraining system at remote site networked to Naval Fleet Combat Training Center–Pacific (Simpson, Pugh, & Parchman, 1990).

support personnel as the instructor presented the course material in the accustomed manner. In this equipment configuration, the instructor could hear the comments of students who spoke into their desk microphones (MIC), and could see, on 12" video monitors, the students at both locations. The students at both locations could see the instructor and the hardcopy graphic-materials picked up by the Elmo easel camera on a 35" video monitor; they could hear, but not see, the students at the other location.

Three lecture courses, rich in terms of the training processes required and with information on the shape and movement of solid objects were experimentally evaluated (Simpson, Pugh, & Parchman, 1990) over a 2-month period with active duty and reservist personnel undergoing required training. A facilitator at the remote site administered and scored the tests that were required, and transmitted the results to the instructor. The courses originated in San Diego with the remote site at San Francisco (Treasure Island). Twenty-one students participated at the originating site while 27 students enrolled at the remote location. Three regular instructors were recruited for this field study and were assigned to one or more of the courses to be taught. The instructors were then brought into a video-training studio to practice teaching in that environment but no measurements were made at that time of instructor attitudes or their skill in that teaching situation. Test scores were compared on performance outcomes for two of the courses, where the maximum possible score was 100 and the passing score was 70, but they revealed no significant difference between the two groups. Performance on one course at the originating site (M = 86.5; SD = 2.9) varied slightly from the scores obtained at the remote site (M = 86.8; SD = 6.2), while the performance-levels on the other course at the originating course (M = 86.0; SD = 4.4) did not differ greatly from the scores obtained at the remote site (M = 82.6; SD = 4.9). However, some informative outcomes appeared in student-attitude ratings of the courses, their interactions with the instructors, and their reports of technical problems with the training system. Student attitude measurements showed: (a) no differences in the appraisal of the instructor; however, students at the remote site rated access to the instructor outside of class hours, as more important; (b) slight difference in the assessment of the adequacy of the physical system; an exception was that students at the remote site rated, as less satisfactory, the loudness and quality of the audio transmissions; (c) assessments of tests and homework assignments were similar at the two locations; (d) no significant difference was seen in the quality of course contents; and (e) the frequency and opportunity for instructor-student interactions during the instructional periods were reported as similar.

When asked whether they would prefer teletraining to the conventional method of instruction, about a third of the students at the remote site were

Table 1.—Student Preference (%) for Teletraining vs. Conventional Training Methods (Simpson, Pugh, & Parchman, 1990)

	Originating	Remote
Video teletraining where instructor is on TV	11	15
Traditional methods of instruction where instructor is physically present in the classroom	37	31
Indifferent between video teletraining and traditional methods of instruction	52	54

firmly committed to the conventional system (Table 1). This percentage was at about the same degree of preference reported by students at the originating site. The majority of students at the remote sites either preferred teletraining (15%) or were indifferent (54%) to the instructional system that was used. When the responses of the students at the remote site are contrasted with individuals at the originating site, negative attitudes toward teletraining were attributed to: (a) fewer opportunities to talk with the instructor (11% vs. 6%); and (b) the sufficiency of the number of opportunities to obtain remedial instruction outside the regular class hours (13% vs. 21%). Regular instructors, qualified to teach the courses, had been given informal training and practiced instructional delivery with the teletraining system and the use of its equipment, in order to enhance student-instructor interaction. In post-course questionnaires completed by two of the three instructors, satisfaction was expressed with the quality and usability of the equipment, effectiveness of the system for the remote sites, and the high level of class-participation by both student groups.

Army Research Institute. The Army Research Institute has supported research studies on the merits of asynchronous computer teletraining systems as media for distance learning. Training on computer-based teletraining systems imposes fewer equipment and telecommunications demands and thus can be operated at much lower cost for instruction than the two Navy teletraining programs. Correspondence courses are the usual options for the Reserve forces who are unable to attend conventional training programs for a variety of reasons. And not to be overlooked, to the advantage of asynchronous training approaches, is the fact that courses by that method are available on a 24-hour demand basis via computer terminals. Though they agreed that such an approach is suitable for training programs that support independent study, Simpson & Pugh (1990) questioned whether that technique would function well as a primary instructional delivery-system. Nonetheless, the Army Research Institute has pursued studies on the feasibility of computer teletraining since 1986 and has accumulated a sizeable body of data on performance, cost, and student attitude toward computer teletraining as an instructional mode. The lessons

learned from this research that can assist training developers to design, conduct, and evaluate computer teletraining courses have been summarized in a series of reports (Hahn, Ashworth, Phelps, Wells, Richards, & Daveline, 1990; Hahn, Harbour, Wells, Schurman, & Daveline, 1989; Harbour, Daveline, Wells, Schurman, & Hahn, 1990; Wells, 1990).

In that computer teletraining system, the structure and content of the residential-course materials were adapted for the home or office environment to provide paper-based readings and problems, computer-based training, and video tapes. The computer teletraining links permitted discussions by the students with the instructor and with each other. Each student was provided with a personal computer loaded with software on course management, communication, computer-based training and tests, word-processing, and a spreadsheet. In addition, the students were given a hot-line phone number in case any hardware/software problems arose. Identical equipment and training on teaching techniques with the computer teletraining system were provided for the instructional staff.

In a typical research project to assess the computer teletraining system, a group of 14 Army Reserve students completed a portion of the Army Engineer Officer Advanced course (Hahn, Ashworth, Phelps, & Byers, 1990). That course work required 66 hours of instruction and covered Army doctrine, engineering topics, leadership, and presentation skills. Performance comparisons were made with all students who took the same courses in residence at the U.S. Army Engineer School over a period of about 32 weeks. Teletraining permitted the student to work with prepackaged learning materials, the instructional staff, and other members of the student group. When time delays would prove to be impractical for a given task, all students accessed the system at the same time and worked together. The instructional staff included a full-time course manager and three part-time instructors. The instructors were given a 40-hr. training course on system operation and teaching techniques appropriate to that system.

Results showed no significant differences in performance scores on the test, homework, and practical exercises taken by the two groups. Comparison of skill-changes, before and after taking the course showed a marginal difference in favor of the students who were in the teletraining program. Survey and interview data on student acceptance of teletraining were collected after course completion, and on-line comments were analyzed to assess acceptability of this instructional approach.

Practically all students who completed the courses preferred teletraining to a correspondence course (Hahn, Ashworth, Phelps, Well, et al., 1990). Very large differences on two measures were reported when residential training was contrasted with independent study: (a) time to complete the course was shorter (2

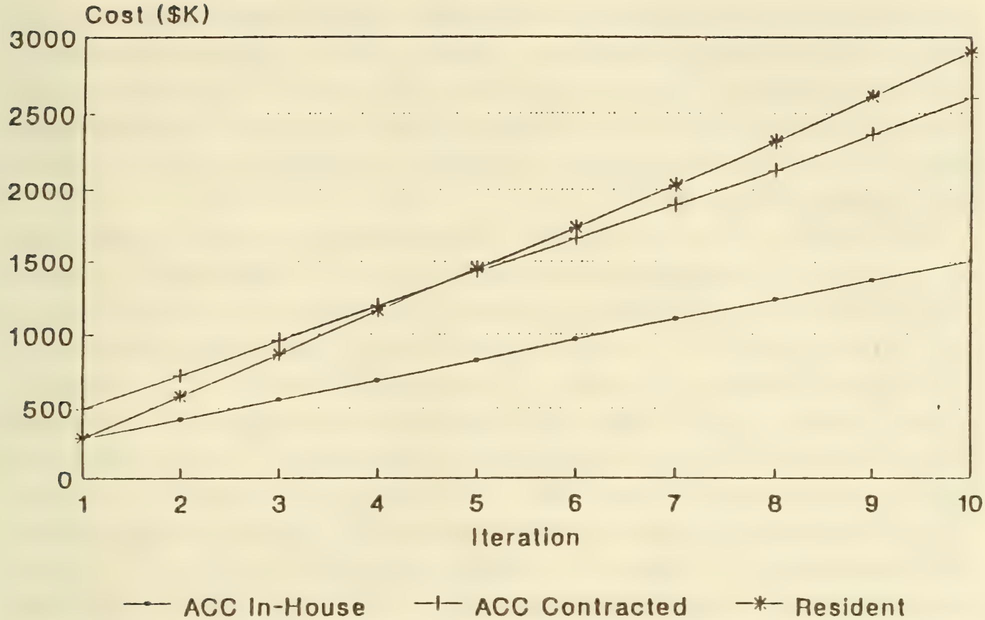

Fig. 4. Cost estimates ($K) for three types of training modes (residential, in-house and contractor-furnished computer teletraining) as a function of the number (N) of course iterations (Hahn, Ashworth, Phelps, & Byers, 1990).

weeks vs. 31 weeks); and (b) percentage of students not completing the course was smaller (5% vs. 36%). Independent study emerges as a highly unfavorable instructional mode. However, those results are similar to other forms of non-residential training, such as correspondence courses. Dropout rates of 65% are not uncommon in Army correspondence courses (Wells, 1990). Cost data for 10 course-iterations were estimated for converting a course to teletraining delivery, based on the following formula, where cost includes equipment purchase, instructor training, and recurring expenses:

$$\text{Cost} = \frac{(\text{class size} \times \%\ \text{throughput})}{\text{cost} \times 100\%}$$

Figure 4 shows that costs for this teletraining system could be amortized over four iterations when training was conducted by outside contractors. In-house developed teletraining had costs similar to resident-training initially, and then decreased immediately during subsequent iterations; the estimated dollar savings in 1990 for in-house training rose by the tenth iteration to about 48%. This savings is substantial when it is appreciated that the Reserve component makes up about one-half of total Army strength.

The Naval Supply System Command has supported the design of a prototype

audiographics teletraining system whose costs were estimated at only $10,000 per site for hardware and software (Young, 1991). In that distance-learning system, a telephone conference call was combined with video imagery loaded into each student's computer. It was reported that satisfactory comparisons were realized in favor of teletraining vs. residential training by students from the Naval Supply environment.

Army Satellite Education Network. When networks are employed for training, they may be characterized by the formation of a highly-skilled staff at a central location, which is another method for cost-control in the development of training programs. The U.S. Army Logistics Management College operates such an educational network, the ASEN, that originates at Ft. Lee, VA, uplinks to a satellite communication system with 58 downlinks throughout the continental U.S. to provide instruction on acquisition management, logistics support, and logistics operations (Brockwell, 1989). Unencrypted one-way video and two-way audio are transmitted to each instructional site which is equipped with a 46" rear-projection TV monitor. Diskettes with digitized images are mailed to the remote sites but their presentation can be controlled by the instructor at the central location over narrow bandwidth phone-lines. This system provides an analog video teletraining system with operating costs that are estimated (Pugh, Parchman, & Simpson, 1991) to be almost 30% less than residential training. It is expected that the analog format for video transmissions will be replaced by a digital system; this latter technology requires a smaller bandwidth and thus, costs will be lower. The Army has circulated a draft standard for video teleconferencing systems that will assure the interoperability of such systems for the secure transmission of video, audio, graphics, and data (MIL-STD-188-131, 1989).

A typical class session on ASEN is transmitted to 7–8 remote sites with a maximum of 30 students at each of those locations; and the duration of a course ranges from 1 day to 3 weeks. Presentations can be taped at the remote site and re-run at dates and times preferred by students. Class-performance data showed that examination scores did not differ significantly from equivalent resident courses; but student ratings indicated that there was a slight preference for residential training over analog video teletraining instruction.

Conclusions

Experience on four distance-learning systems supports the feasibility of teletraining systems in terms of performance and acceptance by adult learners. Field surveys indicate that those systems would be more effective if several

features were enhanced: (a) the downtime due to communication conditions was reduced; (b) greater attention was paid to the maintenance of high-quality audio and video; (c) additional effort was focussed on improvement of student-instructor interactivity; and (d) arrangements for instructor accessibility after class sessions were mandated. The first two issues are technical problems that are tractable but the latter two features require increased attention to instructor preparation or support. Some instructional designers in the Navy (Griffin & Hodgins, 1991) suggest that interactive courseware and distance-learning systems which utilize available artificial-intelligence (AI) algorithms might be combined to provide the individualized interaction that is desired by students. They envision the introduction of procedures that react to incorrect student answers, individualize remediation, and provide training content that is tailored to the style of the learner. They also imagine a schoolhouse equiped with *virtual-image* technology which will allow student and instructor to communicate as if they were face-to-face, via holographic and 3-D stereoscopic simulations. The introduction of AI and virtual-image technologies will complement distance-learning techniques. However, AI training technologists envision future training environments other than the traditional classroom model found in the military training systems that have been examined in the present study. An important research question will be how to meld the best features of the group approach inherent in the conventional classroom with the individualized, active learning that is fostered in AI-based tutoring systems.

Rapid improvements in communications technology at reasonable cost-levels are needed to enhance the physical system, such as compressed digital television which allows for acceptable dynamic video imagery over narrow communication bandwidths. The substantial difference in cost for a two-way vs. a one-way video system is an important factor in the acquisition of these systems that could be reduced by computer networking. However, the overall costs vary widely and are determined in large part by these factors: (a) the number of remote sites; (b) the level of instructional demand at those sites; (c) the complexity of the technical content of the courses; and (d) the initial equipment costs, which can be substantial (U.S. Congress, 1989). Nonetheless, dollar costs have been declining for all of these systems in recent years, and those downward trends are expected to continue (Bailey et al., 1989).

Most of the literature on distance learning has been on case studies with scant empirical evidence (Wells, 1990) and the data are not adequate, so far, to isolate, measure, and determine the features of course content, instructional strategy, and instructor preparation, that are most salient for those training approaches. Unusual demands are placed on the teleteacher to function as a dynamic television personality, as well as a tightly organized, well-paced instructor. Those

factors have been reported (Bailey et al., 1989) as sufficiently different from the requirements of traditional instruction that careful assessment of the distance-learning environment is required to assure effective training performance.

Experimental studies to define optimal features could be conducted economically with hardwired connections between classrooms in the same or nearby facilities to the originating training site. Multimedia workstations for individual students is one of the options for the future; and systems that serve large student-groups might consist of computers, high-definition TV displays, facsimile machines, and push-to-talk telephones. Practical advantages of distance learning are expected from; (a) reduced demand for the construction of residential schools; (b) reduced need for travel for training purposes; (c) increased accessibility to training programs by personnel at remote locations; (d) savings from reduced number of instructor hours that are applied to the design of training materials; and (e) systematic refinement and re-use of course materials will promote higher-quality instruction. No doubt the value of distance learning for a specific instructional configuration will be determined, in part, by assessments of its cost-effectiveness, but the available data for such estimations are presently too sparse. Nonetheless, it is likely that military training will be able to make a strong case for the adoption of distance-learning approaches to meet its critical requirements.

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What a Difference a Sign Makes

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ABSTRACT

It is formally demonstrated that contrary to the general case, the uniqueness of a non-linear differential equation may not be lost when the Lipschitz condition is violated.

Mathematics majors taking an introductory course in differential equations are usually exposed to the well-known result that solutions to such equations are unique provided that a Lipschitz condition is satisfied. A Lipschitz condition means that for a bounded domain D contained in R^2 and a continuous function $f(t, x)$, we have $|f(t, x) - f(t, y)| < M|x - y|$ where $M > 0$ (Ross, 1964, pp. 334 ff.). M is usually called the Lipschitz constant and its existence is guaranteed if $|\partial/\partial x\ f(t, x)|$ is bounded on D. If f is independent of t, this reduces to having $|f'(x)|$ bounded on D. For example, consider the function $f(t, x) = tx^2$ on the unit square $[0, 1] \times [0, 1]$. Now we have $|f(t, x) - f(t, y)| = |tx^2 - ty^2| = |t(x - y)(x + y)| < 2|x - y|$ on the unit square. In this instance, 2 is the Lipschitz constant.

The method of proof for uniqueness usually involves a fixed-point theorem or the method of successive approximations. In this note, two examples of a non-linear differential equation with a unique solution are given when the Lipschitz condition is violated. Furthermore, it is shown that when the sign is changed, an infinite number of solutions occur for each differential equation, illustrating the subtleties involved with uniqueness theorems.

Consider the differential equation, $x' = f(x) = -x^{1/2}$, with initial condition, $x(0) = 0$. Note that $f'(0)$ is infinite at $x = 0$, so the Lipschitz condition is violated at that point since $f'(0)$ is infinite. Also, the trivial solution, $x = 0$, satisfies this equation with the given initial condition and is the only solution. In order to demonstrate this, multiply the equation by $x(t)$ and integrate from 0 to t, to obtain:

$$x(t)^2/2 + \int_0^t x(s)^2 ds = 0 \tag{1}$$

All terms on the left-hand side of (1) are non-negative while the right-hand side is 0. Hence, the trivial solution is the only solution satisfying this equation with the initial condition, $x(0) = 0$.

When the sign of $f(x)$ is changed, then the resulting equation does not have a unique solution (Bellman, 1953, p. 69). In fact, it has a non-denumerable number of solutions given by:

$$\begin{aligned} &x(t) = 0 \quad \text{for} \quad a \le t \le b \quad (a < 0, b > 0) \\ &x(t) = (t - a)^2/4 \quad \text{for} \quad t < a \\ &x(t) = (t - b)^2/4 \quad \text{for} \quad t > b \end{aligned} \tag{2}$$

Here, a is an arbitrary negative number, and b is an arbitrary positive number. Note, that $x(t) = 0$ is a solution as well.

Next, consider the second-order differential equation:

$$x'' + x^{1/2} = 0 \tag{3}$$

It has initial conditions of $x(0) = 0$ and $x'(0) = 0$. The solution to this equation is also the trivial solution, $x(t) = 0$. In order to demonstrate that this solution is unique, multiply equation (3) by $x'(t)$ and integrate from 0 to t thereby obtaining:

$$x'(t)^2/2 + 2x(t)^{3/2}/3 = 0 \tag{4}$$

That equation is satisfied by only the trivial solution, $x(t) = 0$. However, if the sign of $x^{1/2}$ in (3) is changed then the resulting equation becomes:

$$x'' - x^{1/2} = 0 \tag{5}$$

Equation (5) has an infinite number of solutions satisfying the initial conditions, $x(0) = 0$ and $x'(0) = 0$. They are given by:

$$\begin{aligned} &x(t) = 0 \quad a \le t \le b \quad (a < 0, b > 0) \\ &x(t) = (t - a)^4/144 \quad (t < a) \\ &x(t) = (t - b)^4/144 \quad (t > b) \end{aligned} \tag{6}$$

The above solutions satisfy the relationship:

$$x'(t)^2/2 - 2x(t)^{3/2}/3 = 0, \tag{7}$$

which is analogous to equation (4). Again, by changing the sign in equation (4), a non-denumerable number of solutions to the given equation is obtained.

Thus, uniqueness may occur even when the Lipschitz condition is grossly violated, although in general this is not the case.

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Effect of Cyst Age, Media, pH, Temperature, and Time, on Excystment of *Blepharisma stoltei* Isquith

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ABSTRACT

The effects of various media on excystment processes of *Blepharisma stoltei* were studied using four different media: Cerophyll, wheat germ infusion, distilled water, and Brandwein's buffer solution without light over 72 hr. Excystment optimally occurred at 26° C in wheat germ infusion and to a lesser extent in Cerophyll but not in distilled water or Brandwein's solution. The effective pH range for excystment was 7.2–7.8 with an optimal value at 7.7. The presence of suitable bacteria or their metabolic products appears to contribute toward the process of excystment. Other factors involved are the age of the cysts since their creation and time. Excystment optimally occurs within 24–48 hr and continues to a lesser extent in the following days depending upon the pH and nutritional value of the medium in question.

Introduction

The existence of the resting cyst of *Blepharisma lateritum,* a reddish to pink ciliated protozoan, was first noted by Cienkowsky [1]. A resting cyst is a stage in the life cycle of a protozoan, where the organism secretes a wall about its self several layers thick. Cysts may be produced under inclement conditions or for reproductive purposes. Later investigations [2–11] were devoted to studies of various morphological and cytochemical aspects of cystation in a variety of strains of *Blepharisma.* The conditions leading to the formation of cysts have been examined in various ciliates [12–15]. Some of the factors that affect excystment in *Blepharisma* have been only partially studied by Giese [16] using *B. americanum.* Past investigations used a variety of different media to grow this ciliate [16–19]. Growth and excystment were noted in polyxenic cultures using Cerophyll and wheat germ infusion but did not occur in distilled water or Brandwein's solution [18]. The purpose of this study was to investigate the effects of cyst age, different culture media, temperature, time and pH on the excystment of *Blepharisma stoltei.*

Materials and Methods

Blepharisma stoltei (Federsee, Germany strain) Isquith 1967 was maintained in finger bowls containing bacterialized infusions of 0.3% weight/volume (w/v) Cerophyll. The cultures were held at room temperature without light and subcultured weekly. *Blepharisma stoltei,* in Cerophyll, formed cysts on a regular basis within three weeks.

To determine the effects of different media on excystment, 50 cysts, washed 3 times in two-day old Cerophyll, were placed into wells of a Falcon multiwell sterile, plastic, tissue culture-dish containing 10 ml of (1) wheat germ infusion (WGI) [i.e., 0.3% Cerophyll (w/v) plus one distilled water washed wheat kernel]; (2) 0.3% (w/v) Cerophyll; (3) Brandwein's buffer solution (BWS) [20]; or (4) distilled water. Duplicate sets were used. The cysts were placed in a moist chamber at 26° C for 24, 48, 72 and 96 hr. in the dark. Ten trials were used in each medium. Each day, the number of completely excysted trophozoites were counted and removed. The ratio of the number of excysted forms per total number of viable cysts was used to compute the percent excystment per medium.

The effect of pH on excystment was determined by using 5 ml. of fresh Cerophyll media contained in wells of multiwell tissue culture plates. Thirty cysts, handpicked through the use of micropipet and a stereo-dissecting microscope, were introduced into each well. The plates were incubated in the dark at 26° C and checked at 24, 48 and 72 hr. Alloquots of fresh Cerophyll were adjusted to pH 4, 5, 6, 7, 8, 9, 10, 11. Unaltered Cerophyll (pH 5.8) and distilled water (pH 5.8) served as controls. The experiments were performed twice. Cysts were also introduced into fresh culture media and the pH checked daily.

The effects of temperature on excystment in each medium were also determined (using the same procedures described for the study the effects of different media) at 5, 14, 20, 26 and 34° C following 24, 48 and 72 hr. in the dark. There were ten trials in each medium at each temperature.

Cysts used were a month old except in one instance where cysts were 5 days old.

The significance of the resulting data was statistically analyzed using GML Analysis of Variance (ANOVA).

Results

No excystment occurred in distilled water or BWS. WGI induced a significantly (p = .05) larger percentage of excystment (M = 9.7%$^{-day}$, SE = .59) than did Cerophyll (M = 1.8%$^{-day}$; SE = .63). Best results were obtained for excyst-

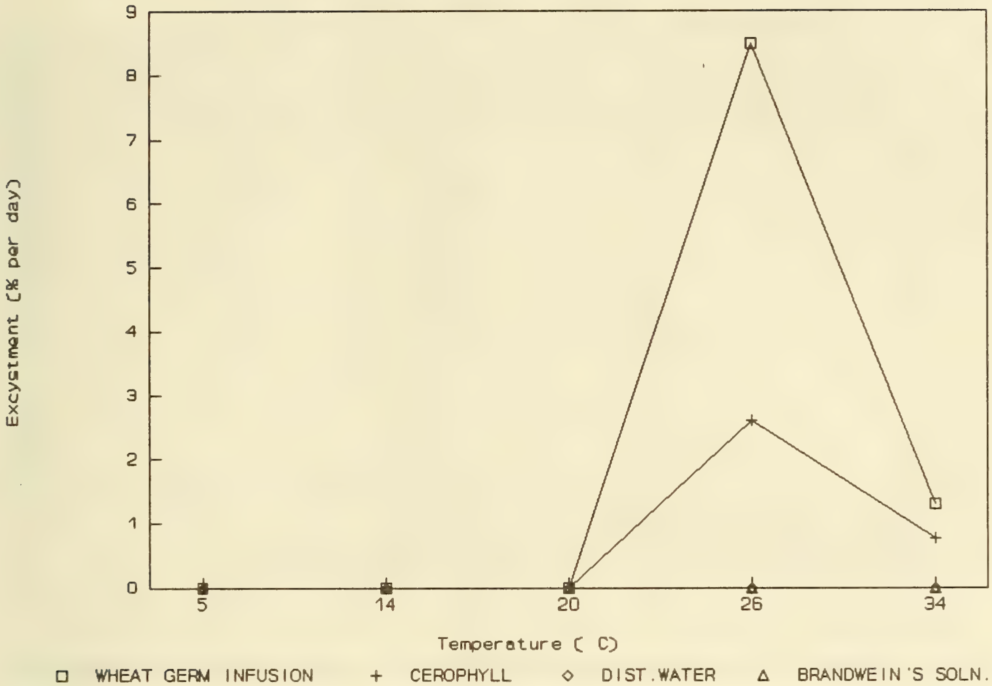

Fig. 1. The effects of temperature on the percentage of excystment of *Blepharisma stoltei* in four different media.

ment at 26° C for both media (Fig. 1). No excystment was observed at 20° C for either medium. At 34° C, the differences between the two media were not statistically significant but they were at 26° C (p = .05).

Under preliminary conditions the greatest amount of excystment occurred when pH was 6.3–7.2. Under the conditions of this experiment the pH of Cerophyll was adjusted to eight different values on day 0 and the cysts were put into the medium (Table I). After 24 hr. the greatest amount of excystment was found at pH 9. Excystment was seen between pH 5–10 but the percent of excystment was not statistically different from the average. In all adjusted media (pH 2–11) after 24 hr. the pH values tended to swing toward equilibrium settling near 7.3. Extremely low (<5.0) or high (<10.0) pH values were detrimental to excystment.

Fresh Cerophyll with wheat germ kernels had an initial pH of 5.8. Following incubation for 24 hr., the pH was 7.2. After 48 hr., the pH of Cerophyll was determined to be 7.6 ± .1. During the following 2 to 3-week period, the pH of most cultures appeared to increase slowly until encystment occurred and remained at pH 8.0 ± .2.

In general, *time* had a highly significant effect on the % excystment. A media x

Table 1.—Effect of pH[1] Levels of Cerophyll on Excystment of *Blepharisma stoltei*

Adjusted Medium Levels	Mean % Excysted		pH of Medium	
	Day 1	Day 2	Day 0	Day 2
Ctrl A[2]	0.00	28.33	5.8	7.65
Ctrl B[3]	0.00	0.00	5.8	5.80
1	0.00	0.00	4.0	4.60
2	0.00	3.33	5.0	7.25
3	1.85	10.93	6.0	7.45
4	1.72	6.90	7.0	7.75
5	2.87	22.67	8.0	7.70
6	10.00	26.67	9.0	7.65
7	0.00	21.71	10.0	7.80
8	0.00	0.00	11.0	7.85
M	2.06	17.22		7.26
SD	3.18	9.27		1.02
Min	0.00	3.33		4.60
Max	10.00	28.33		7.85

[1] The pH was adjusted before the cysts were put into the media.
[2] Control A contained Cerophyll as a culture medium with the pH unaltered.
[3] Control B contained distilled water with *B. stoltei* with the pH unaltered.

time first-order interaction was highly significant ($p = .05$) demonstrating the lack of independence between the two variables.

Finally, percent excystment using one-week old cysts was significantly different (3.4 times greater) from that of cysts taken three weeks after encystment.

Discussion

Excystment of *Blepharisma* occurs in cultures which facilitate bacterial growth. Bacteria probably influence the initiation of excystment and the buffering and stabilization of the media pH. The growth of bacteria, like other cells, is time and temperature-dependent, and specific bacteria can only grow under certain ranges of temperatures. The influence of bacteria on excystment has been demonstrated in *Didinium nasutum* [12, 14]. Excystment of *Nassula ornata* was studied by Beers [21] who introduced cysts into 0.1% proteose-peptone, previously inoculated with bacteria taken from the surrounding environment. McLoughlin [6] found that a whole milk and horse-dung infusion easily induced excystment in his cultures of *Blepharisma.* Strickland and Haagen-Smit [22] used a simple mixture of 0.3 M ethanol and 10^{-4} M potassium phosphate to induce excystment in *Colpoda duodenaria.* Giese [16] tried this simple concoction on *Blepharisma* with limited success.

Osmolality, pH changes, and differences in quantities of potassium and phosphate were indicated as major factors in the excystment of *Vorticella micros-*

toma [23]. Jefferies [24] noted that fructose diphosphate, several amino acids and citric acid may act as excysting agents for *Pleurotricha lanceolata.* Demar-Gervais and Génermont [25] found that *Fabrea salina* excysted at 37° C. They also indicated that during excystment a chemical signal is produced promoting excystment in other cysts. Experimentally, Demar-Gervais and Génermont also demonstrated that trypsin promotes excystment in *Fabrea salina.* The undetermined chemical inducer is believed to be a proteolytic enzyme and induces an unknown step of the excystment process. Singh [13] indicated that a bacterial environment is necessary for excystment of many kinds of protozoa.

One more point to consider is the number of organisms that excyst in laboratory cultures. More organisms form cysts (encyst) than are released from the cyst (excyst) under the culture conditions used in this study. Considering that *Blepharisma* cultures are far from sterile and also that newly encysted forms do better than older ones, there is the possibility that a parasitic fungus is responsible for the low numbers of viable cysts. Foissner and Foissner [26, 27] reported parasitism of cysts of the hypotrich *Kahliella simplex* by a *Ciliomyces spectabilis,* a member of the Lagenidiaceous fungi. Although this author has not personally observed a fungus in the cysts of *Blepharisma,* many cysts were found to be empty during excystment experiments.

The majority of reported species of *Blepharisma* are inhabitants of fresh waters. These ciliates are subject to a variety of natural and unnatural environmental fluctuations depending upon the seasons and human-oriented activities, e.g., acid rain and pollution. Like many protozoa, *Blepharisma* meet changes in food content, pH and temperature, by forming numerous cysts. When more favorable conditions return, some of the surviving inactive cells redifferentiate, emerge from the cyst and resume a vegetative life. This study has attempted to define some of the limitations upon excystment faced by this ciliate.

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Penicillin Production Saga Recalled

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ABSTRACT

The epic journey of Nobel laureate Sir Howard Walter Florey and his associate, Dr. Norman Heatley, to the U.S. in 1941, seeking help in making enough penicillin to confirm their promising clinical evaluation studies, is described. The trip ended with spectacular success even though Florey on returning to England, believed he had failed in that mission. The Northern Regional Research Laboratory (now the National Center for Agricultural Utilization Research) of the U.S. Department of Agriculture was deemed to be the best place where the production problem could be solved, and indeed, two major research discoveries at that laboratory provided the basis for successful large-scale manufacture of the drug.

This short note summarizes some key events in U.S. Department of Agriculture (USDA) involvement in the development of penicillin and extends the remarks of Moberg (1991) concerning an honor that came recently to Norman Heatley. It is most heartening that Oxford University has conferred on Heatley an honorary degree of Doctor of Medicine. The honor is well deserved for Heatley played a crucial and successful role in the penicillin studies at Oxford, headed by Howard Walter Florey. Although Heatley, like others (Bickel, 1972), was not able to produce penicillin in large amounts, he succeeded against overwhelming odds in making enough of the drug to establish its great potential in treating bacterial diseases.

Further studies needed to confirm this early work were seriously stymied by the very low yields of penicillin produced by the mold *Penicillium notatum.* It was at this point, in June 1941, as related by Moberg, that Dr. Florey together with Dr. Heatley came to the U.S. seeking help in making enough of the drug to complete their promising laboratory and clinical work. And thus began one of the great science sagas of modern times.

Shortly after they arrived in the U.S. I became a link in a chain of circumstances which quickly took these men to the one place in the world where the

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basis for a major break in the problem of penicillin production already existed although no one knew it at the time. Dr. Heatley was directly involved and I think the story needs recalling. In the end a great new penicillin industry was created so their trip to the U.S. was a huge success even though at the time Dr. Florey returned to Oxford he felt that his trip was a failure.

In early July 1941, Florey and Heatley concluded their harrowing war-time trip from England to New York City. There was barely enough time to report their recent findings to the supporting Rockefeller Foundation officials before moving on to New Haven over the July 4 holiday which enabled Dr. Florey to visit his two children who were staying with the Fultons for the duration of World War II. John Fulton and Howard Florey were great friends dating back to Rhodes Scholar days at Oxford and when Dr. Fulton heard Florey's story nothing could stop him. In a few days he had his English visitors in Washington, DC where they contacted Dr. Ross Harrison, Chairman of the National Research Council Board, who immediately put them in touch with Dr. Charles Thom, a most noted mycologist in the U.S. Department of Agriculture (USDA). Dr. Thom seemingly knew everything that was going on in his field of expertise and without any preliminaries brought his English guests to see Mr. H. T. Herrick, Assistant Chief of USDA's Bureau of Agricultural and Industrial Chemistry. But he found me there instead. Much against my will I was spending the entire month of July in Washington, DC, backing up Mr. Herrick while he traveled.

There we were: Dr. Florey, Dr. Heatley, and Dr. Thom, along with me. These two Englishmen were our guests that hot afternoon of July 9, 1941. It was sticky hot and we had no air-conditioning. Dr. Florey was the spokesman. He quickly explained their need for a large supply of penicillin to complete their clinical studies. I had never heard of penicillin before that moment but I never doubted his statement about this miraculous substance, quite probably because I wanted it to be true. Before he finished my mind was made up. Mold fermentation research had been my special field of interest from 1930–39 at our Bureau's Color Laboratory near the Pentagon site across the Potomac River in Virginia. My research associates of those years had been transferred to the newly established Northern Regional Research Laboratory (NRRL) of USDA in Peoria, IL in late 1940 when those facilities became available. As I wrote later (Wells, 1975), it was in my view the one place in the world where the job could best be done and it was there that the penicillin production problem must be attacked, and that was my proposal. Dr. Florey accepted at once! My immediate telegram to Dr. Orville E. May, Director of the NRRL, was written while they were with me and the next morning I was able to tell Dr. Florey that all was in readiness for their visit. Florey and Heatley arrived in Peoria at noon on July 14, 1941, just a couple days after meeting with me in Washington and that same afternoon,

research on the improved production of penicillin began. Dr. May insisted that work should first be undertaken to improve the penicillin yields. Dr. Robert Coghill, Head of the NRRL Fermentation Division, was placed in overall charge of the project and the immediate Laboratory phase was assigned to Dr. Andrew Jackson Moyer, a former associate of mine at the Color Laboratory in Virginia. Dr. Heatley stayed on at the NRRL for several months to work with Moyer and others to teach his penicillin assay method and for other reasons.

Poor Heatley! His assignment to work with Andy Moyer was an extremely difficult one. Moyer was totally, one hundred per cent, anti-British for he believed as did many others at that time that Winston Churchill was dragging the U.S. into World War II. To this day many Americans believe that was true. So it is apparent that Heatley was placed in a most uncomfortable situation. Those of us who had worked with Moyer for years knew that his bark was worse than his bite and somehow, we and Heatley found satisfactory accommodation. In spite of these personal asides all of us recognized Dr. Moyer's expertise in nutritional mycology.

I must back up a moment here to explain that in 1937 during studies on the sorbose fermentation at the Color Laboratory, due to a shortage of funds, we sought and found a low cost substitute for yeast extract used in our medium. This substance was known in industry as *corn steep liquor,* a byproduct in the wet milling process for the manufacture of corn starch. Dr. Moyer was a close witness to this work and used it in at least one mold fermentation study.

Within a short time after the penicillin problem was assigned to him he demonstrated that the addition of corn steep liquor to the British medium in the optimum amount greatly increased the penicillin yield. It was a miraculous thing and it provided a tremendous boost to the penicillin project when, on Dec. 17, 1941, Dr. Coghill was able to report this finding at an industrial conference in New York. Up to this point the fermentation industry people, although sympathetic to Florey's needs, were unable to commit themselves to making penicillin because of the poor yields. With this new information, the interest of both industry and government agencies was assured. Production of penicillin by means of a surface fermentation was undertaken (Bickel, 1972).

But even with this great improvement in penicillin yields there was in railroad parlance a *SLOW SIGN.* The surface fermentation was inherently slow and the overall yields of product needed improvement. The USDA researchers at the Peoria laboratory knew there was a better way. Beginning in 1930 at the Color Laboratory, research on *submerged* mold culture fermentation was undertaken and by 1937, successful large-scale fermentation equipment had been built and two fermentation processes had been developed on a pilot-plant scale to make gluconic acid and l-sorbose (Wells, Lockwood, Stubbs, Roe, Porges, & Gastrock,

1939; Wells, Lynch, Herrick, & May, 1937; Wells, Moyer, Stubbs, Herrick, & May, 1937).

There was nothing really new about submerged fermentations. Far from it. Man was into this thing in prehistoric times when he made his first intoxicating beverages by means of the alcoholic fermentation. But it was new for mold fermentations until it was done in 1937 by USDA fermentologists. So an organism that would grow in a submerged environment and produce large amounts of penicillin was sought and in July 1943 it happened. Through the prolonged efforts of Dr. Ken Raper at the NRRL, a culture of *Penicillium chrysogenum* was obtained right there in the fruit market of Peoria that met these qualifications. Later this mold was tailored by X-ray and other means in other research institutions to give very high yields of penicillin (Kauffman, 1975; Raper, 1978).

These two major research developments: (1) the use of corn steep liquor in the medium; and (2) the use of the tailored mold *Penicillium chrysogenum* were quickly adopted by industry which then was able to make its giant contributions to the effort. Throughout this period of development the NRRL was able and did relay new research information to industry by means of conferences so there was no delay in transferring and using this vital information. Thus technology transfer was at its best decades before this modern term came into use.

From the time of my meeting with Florey and Heatley on July 9, 1941, there was a continued sense of urgency about penicillin. Thus it came about that massive amounts of this miracle drug were available for our armies on D-Day, June 6, 1944, a bit less than three years from our first encounter with the problem. It was a fantastic achievement in which everyone who participated can take pride. It ranks in the view of many, right along with the war-time developments of radar and the atom bomb. In addition to other prestigious awards the Northern Regional Research Laboratory was named an historic site by the American Institute for the History of Pharmacy and the Illinois Pharmacists Association on Sept. 5, 1980, for its contributions to the large-scale production of penicillin. The bronze plaque presented that day reads as follows:

> *On this site the Northern Regional Research Laboratory, USDA, made key contributions to the development of large-scale penicillin production (1941–1946). These included the introduction of submerged culture fermentation, the use of precursors to produce more effective penicillin, and the discovery of a mold strain more productive of penicillin.*

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Transformation Dynamics in Complex Systems

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ABSTRACT

For more than one hundred years, researchers of psychological theories of learning, economics, human factors, education, and management, have described the processes of development in individuals, firms, technologies, and nations, as simply monotonic. That assumption was adopted even though it did not always predict and adequately describe those development processes. When the structures in industry, professional education and training, and society, changed slowly, monotonic models were more or less acceptable. Now, the success of dynamic systems, like advanced manufacturing, retraining, and progress in the former Soviet Union, eastern Europe, and other countries, depends on a process of deep transformation for the very structure of those systems. Old theory is not sufficient in those cases, transformation dynamics theory which studies changes in complex system structures is required to help in the prediction of the dynamics of efficiency, to minimize inevitable losses, and to speed up the attainment of the highest levels of productivity, quality, reliability, and safety. A newly discovered law of transformations is described as a fundamental basis for that new transformation theory.

Traditional Monotonic Models

Monotonic dynamics models came from traditional psychological learning theory. Studies on learning have been a central problem in world psychology. Systematic experimental research on learning processes was initiated by H.

[1] While he was critically analyzing and generalizing 20 years of experimental data on transformation learning processes, Y. Venda discovered the Law of Transformations. He was tragically killed, at the age of 22, on August 9, 1991, at a summer camp during a tornado. This paper is dedicated to his memory.

Ebbinghaus (1885). His numerous experiments led him to identify the existence of monotonic (actually exponential) regularity in learning dynamics. E. L. Thorndike (1898) and C. L. Hull (1943) confirmed that regularity. Many subsequent experimental studies and mathematical models of learning and development processes confirmed the same monotonic shape of the dynamic curves (Atkinson & Crothers, 1964; Bower, 1961; Bush & Mosteller, 1955; Estes, 1950, 1959; Greeno, 1967; Luce, 1959).

Monotonic learning curves were generally accepted in behavioral science. For example in a handbook on experimental and design techniques in engineering psychology, Chapanis (1959) recommended monotonic exponential approximations for any kind of experimental data on individual training. On this basis Zarakovski, Korolyou, B. M., Medvedev, V. I., & Shlaen, P. Y. (1977) proposed to compute learning curves based on three or even two empirical points. As a result most authors in the last 50 years considered dynamics in development as very simple, i.e., monotonic and exponential. The experiments by Bryan and Harter (1899) on training of operators using telegraphic code, where intermediate plateaus had been found, were ignored because no theory or regularity was given for these unusual phenomena. A short explanation, with a hypothesis regarding plateaus as indicators of changes of the observer's strategies was given by Woodworth (1938). Hence only two types of learning dynamics curves were usually considered during the early years: monotonic exponential, and monotonic with intermediate plateaus. Monotonic exponential dynamics of development was regarded as classic and universal.

From Models of Monotonic Statics to Monotonic Dynamics

Monotonic exponential models were widely used not only in analysis of individual learning processes, but in many other areas of science and practice. For example, many economists tried to predict dynamics of the financial state of companies and industries as monotones exponential processes. They found that long term predictions up to 30 years or more could be more or less modeled with that type of progress curve. However attempts to use traditional monotones curves for prediction of shorter periods were unsuccessful. Yanch (1974) named middle-term prediction periods as *difficult periods.* One could imagine how many companies fell into bankruptcy with this primitive modeling and prediction of dynamics by monotones processes. Monotones learning theory has made some people unhappy. Teachers and coaches expect steadily increasing academic and athletic success. Any declines lead to such dramatic results as removal of non-performing people. Wrong theory led to wrong decisions. The

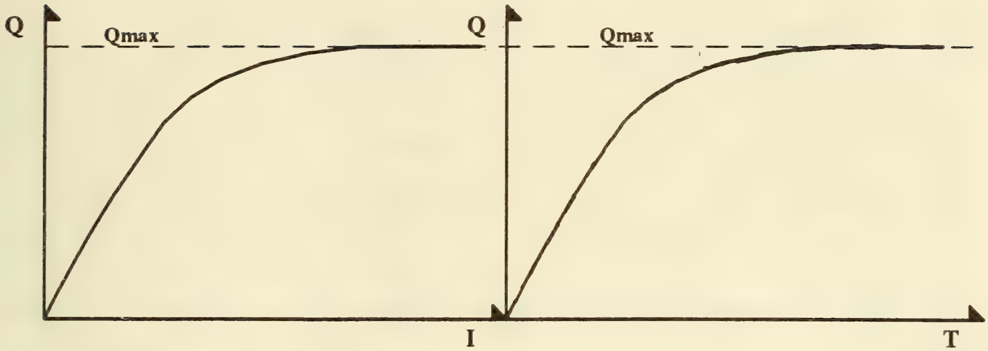

Fig. 1. Illustration of the Fitts' Law (left side) and monotones dynamics as its consequence (right side). Q = efficiency of performance; I = information volume perceived; T = time.

same trouble was also common in science and industry. Temporary declines of efficiency are inevitable and play a positive role in the development of the individual, firm, technology, science and every complex human-machine-environment system. Why has monotonic development dynamics hypnotized people for such a long time? There is an experimental basis for the phenomenon. A theoretical basis for monotones exponential theory of dynamics was provided by Fitts' law (1954), illustrated on the left side of Fig. 1. The monotones influence of the volume of information perceived by an observer's efficiency of information processing was stated by Fitts. The static characteristic of that influence is monotones. It is easy to understand (monotones theories are very attractive because they are easily comprehended) that dynamics also will be like monotones. Indeed a learning process is always based on gradual increasing of information displayed and perceived by the individual. According to Fitts' law the efficiency of the performance studied should also increase gradually. Zarakovski et al. (1977) have drawn this simple logical conclusion as shown on the right side of Fig. 1. After reaching the single maximal level of efficiency (Qmax) determined by Fitts' law, further learning will not affect efficiency. The same authors adopted an over-simplification of learning theory leading to approximations of the monotones learning curve with only three, and then just two, experimental data points. That simplification is far from real learning and development dynamics in individuals and human-machine-environment systems, and monotones models are wrong and useless in many important practical cases.

From Fitts' Law of Monotones to a Law of Transformations

Sheridan has noted that Fitts' model accords with the experimental data in a number of relatively simple studies, but cautions that "like so many elegant

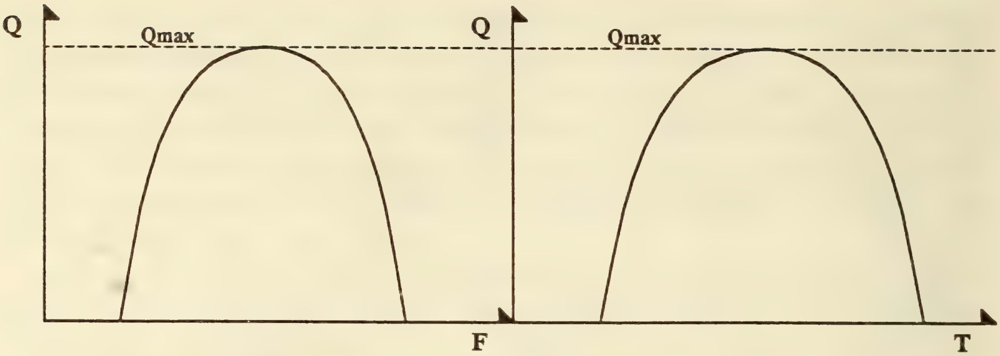

Fig. 2. The law by Yerkes-Dodson and F. W. Taylor (left side) and its consequence as a bell-like shape of performance efficiency dynamics (right side). Q = efficiency; F = ergonomic factor; T = time.

models for human behavior, Fitts' model breaks down for more complex manipulations" (1992, p. 123). In the very beginning of this century Yerkes and Dodson (Woodworth, 1938) and F. W. Taylor (Freivalds, 1987; Konz, 1990) found that every human or animal performance has an optimal condition for maximal performance efficiency. That means that if efficiency of information processing (understanding of texts, decision making, diagnosis) is a bell-shaped function of the information volume perceived, it can not be constant when information volume surpasses some certain, optimal level for maximal efficiency. Further increasing of information volume will lead to decreases in performance efficiency. Hence, performance efficiency dynamics for gradual information volume increases will also have a bell-like shape (Fig. 2). Several series of experiments (Venda, 1990) were conducted that examined hypotheses about non-monotonic behavior in the efficiency of human performance:

1. Observers were asked to identify words of 8 letters' length. Different, randomly (for static characteristics), and gradually (for dynamic), increasing numbers of letters were displayed: from 0 to 90. The probability of correct answers changed as shown in Fig. 2. This bell-like shape of the Q function meant that Fitts' law was not correct for volumes of information greater than optimal. In other experiments (Venda, 1989–91) the optimal volume was equal to the length of the word, i.e., 8 specific letters. If more than 8 letters were displayed, the exact word became masked. Masking was greater with further increases in the number of letters. After 15–17 letters the probability of a correct answer was practically equal to zero.
2. Observers were asked to read words with a length of 8 letters (Venda, 1990). All letters were displayed, but with special fonts making reading more or less difficult, so that the observers were reading by separate letters, by syllables and by whole words. Eye movements were recorded. In another series of experiments, text by separate letters, syllables and words was displayed on the computer screen. In addition, text moving on the screen with different speeds was displayed for reading by letters, syllables and words. The static characteristic curves for eye movements during three strategies of reading (letter, syllable, or word) as a result of the experiments are shown

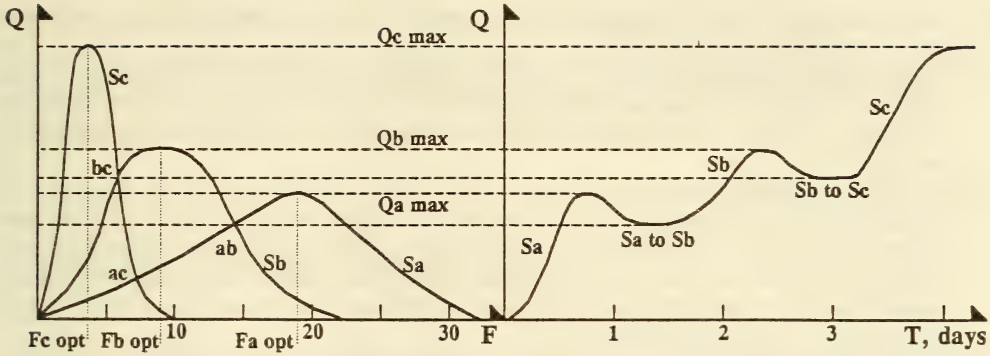

Fig. 3. Transformation dynamics in information perception: characteristic curves of reading strategies: Sa = reading by letter; Sb = by syllable; Sc = by word (left side); and transformations of those strategies (right side). Q = efficiency (probability of successful trial divided by time spent); F = ergonomic factor (number of eye movements during perception); T = time (Venda, 1990).

in Fig. 3 (left side). The right side of Fig. 3 shows learning curves with changing strategies from Sa to Sb and then into Sc or directly from Sa to Sc. These characteristic curves are static because the curves display the influence of a randomly changed factor, not a process in time. The characteristic curves were obtained by selecting data (Q and F) for different performance strategies. For example, analysis of eye movements during information perception enables us to classify each strategy of reading.

Fundamentals of Transformation Dynamics Theory

Several important findings led to a fundamental theory of transformation dynamics:

1. The same human performance could be accomplished with different strategies, and every strategy has its specific characteristic curve, i.e., a correlation between performance efficiency (or other criteria) and ergonomic (psycho-physiological) factors of performance. The same items could be produced by using different technologies and management structures.
2. If an ergonomic, economic, technological or management factor is increased gradually, monotonically, and the performance has only one strategy, the dynamics of efficiency (learning curve) will have bell-like shape.
3. If an ergonomic or some other factor is increased gradually, monotonically, but different strategies are used in practice, efficiency changes to a wavy-like process, with monotones, exponential phases of development for every concrete structure-strategy, and efficiency decreasing when a previous strategy is transformed into a new one.
4. So, in addition to monotones exponential learning curves discovered by Ebbinghaus (1885) and learning curves with intermediate plateaus discovered by Bryan and Harter (1899) wavy-like learning processes were found. Woodworth (1938) suggested that the phenomenon of plateau arises because observers change their cognitive strategies while executing the task. The same explanation can be used in our case, but

the difference between strategies (distance between their optimal F values) needs to be big in order to have a wave.

5. Transformation of one strategy to another depends on the level of efficiency (Q) and value of factor (F) common to both strategies. In Fig. 3, transformation states are illustrated by the crossing points of the characteristic curves for the strategies Sa, Sb, and Sc.
6. Psycho-physiological structures which are the bases of the respective strategies of performance have some common parts. When a transformation is starting, that part which is specific to the structure is eliminated. Only the common part remains. Obviously the efficiency of this part is lower than that of the whole structure. Subsequently, on the base of this common part a whole new structure is synthesized and the efficiency rises to a higher level.
7. Sometimes, performance structures include many different levels of the human organism. Barabash (1982) of the Novosibirsk Branch of the Russian Academy of Science showed that the training of astronauts affects not only the psycho-physiological level but also biological and cell levels of their organism. Transformations of structures can be, at times, very fast (in our experiments it could take only minutes) but sometimes, very slow. It is well-known that the training of athletes takes many years. We suggest that transformation strategies are important not only in the direction of ever-increasing complexity, efficiency and achievement, but also in the reverse case of reduction in complexity, efficiency and achievement, such as in factory downsizing, de-automation to meet reduced demands, and retirement of highly motivated and skilled staff. It is important not to slide down too fast on the left side of the curve. Previously challenged individuals have met untimely illness, depression or even death, once challenge is removed (e.g., retirees from executive levels, or former athletes).
8. Examples have been found of such wavy-like processes in physics, chemistry, engineering, non-linear control theory, metallurgy, optics, electricity, social processes, as well as in economics (Venda, 1990). Those transformation dynamics processes have similar mechanisms and should be studied with the single methodology of transformation dynamics (Y. Venda has proposed the name, Transformatics, for this future science).

Law of Transformations

Y. Venda worded the Law of Transformations as follows: *Transformations of structures-strategies of any system go through states common to the previous and following structures-strategies.* By *system* he meant a complex unit with constant components and energy-material resources. By *structure* of the system he meant the regularity of mutual adaptation processes between inner components of the system. The regularity could be displayed as a technological scheme (technological structure), scheme of organization hierarchy (management structure), sequences of operations (algorithm structure), structure of the control system (dynamic links between parameters with transferring equations), and the tree structure of a work operation. By *strategy* of the system he meant the regularity of mutual adaptation of the system with its enviroment (the charac-

teristic curves at the left sides of Figures 2–5 display different strategies). Hence, strategy depends on interaction between internal structures and external conditions. It is very important always to study the pairs: the structures and respective strategies of the system.

Transformation Dynamics in Decision Making

Y. Venda was interested in testing the Law of Transformations in many different systems and conditions. He proposed to study transformations in learning as a long-term psychological and decision-making process. He started to analyze my old experimental protocols, and was especially interested in natural, field, and industrial experiments.

Special emergency experiments were devised at Moscow's fossil power plant #21. At that time complex equipment for the control room of the plant was designed and implemented (Venda, 1982). Moscow Power Plant Headquarters gave special permission for the conduct of emergency experiments for objective studies of efficiency, reliability and safety of control room equipment, and analysis of the performance of human operators under normal and emergency situations. Ten emergency situations were created during night time (between 2 and 5 AM). Suddenly and secretly, without the knowledge of the operators, important technological equipment like working feed water pumps, air and dust fans, and fuel lines, were turned off. Operators were supposed to recognize, diagnose, locate and eliminate those emergencies with information obtained from annunciator-flashing labels, mnemonic schemes, and computer displays. Five operators participated in the experiments, each operator two times. All commands, comments, inquiries, operations, motions, and eye movements, were recorded with movie camera, computer, and telemetric psycho-physiological instruments.

Three cognitive strategies were found among operators: Sa—perception of information by separate elements; Sb—perception of information simultaneously by small chunks (2–11 functionally connected elements); and Sc—perception of information simultaneously by big chunks (20–50 functionally connected information elements). Characteristic curves of these strategies and their transformations during decision making processes are shown in Fig. 4. When different strategies are used simultaneously, in parallel, to solve especially complicated, multi-factor tasks, a special group of different specialists with the aid of a Hybrid Intelligence system can be implemented. The system would use individually adapted information displays (Venda, 1990).

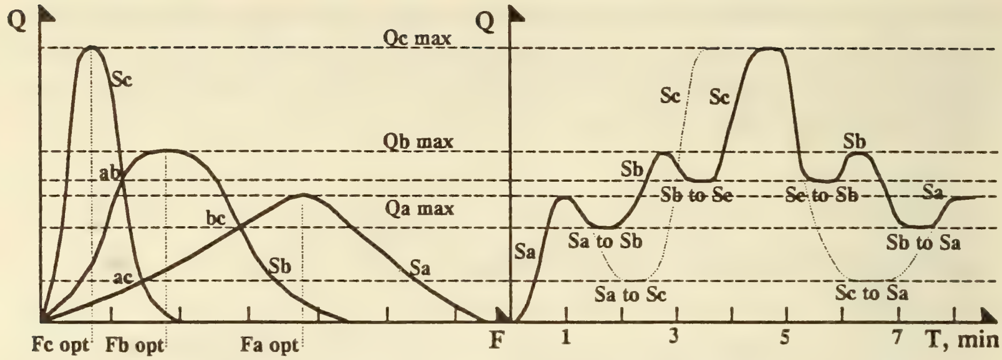

Fig. 4. Transformation in human operator performance under emergency conditions at a power station: characteristic curves of operator information-perception strategies (Sa = by separate elements; Sb = by small chunks; Sc = by whole technological units) (Venda, 1982).

Transformation Dynamics in System Safety

It was found during the emergency experiments that it is especially important to teach operators not only to perform main control strategies but to quickly and easily transform one strategy to another, e.g., to transform a strategy and psycho-physiological state adequate for a normal control situation into one which is adequate for a suddenly occurring emergency. Fig. 5 (right side) shows processes of transformations of a normal strategy. Sn, into an émergency (alarm) strategy, Sa, and back into Sn. The Factor F is the relative level of psycho-physiological strain as a complex parameter of electrical brain activity (in alpha, beta, and delta intervals), average number of eye movements per minute; or angle of movement and fixation duration of the eyes (Venda, 1982).

To consider the multilevel character of human structure it is important to explain these phenomena:

1. For individuals (as well as other complex systems), structures and strategies in their explicit representations in the processes of mutual adaptation, are plural. Human

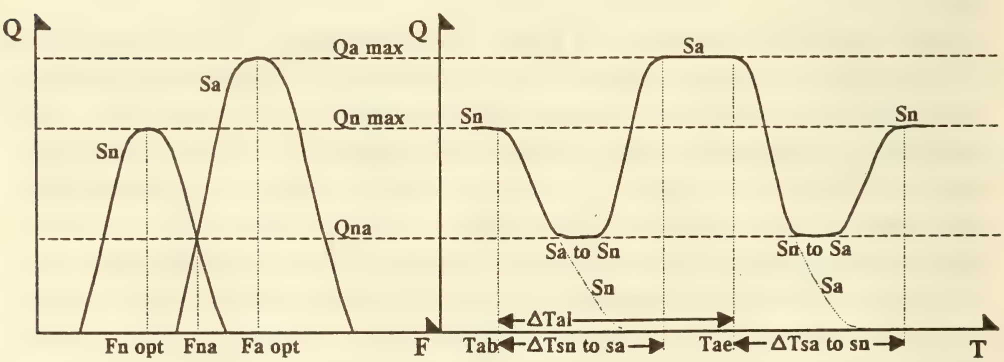

Fig. 5. Transformation dynamics of operator's strategies at the start and end of emergency situations. Sn = strategy in normal situation; Sa = strategy in alarm situation; Q = efficiency; T = time.

performance can be achieved with several different structures and strategies. Effective and safe performance is based on adequate structure and strategy.
2. Human structures and strategies are discrete. There are essential intervals between values of every factor of mutual adaptation efficiency and complexity that is optimal for different structures-strategies. The same individual can respond very differently to the same information in normal and emergency situations.
3. A human operator well trained to work separately in normal and in emergency conditions may fail in the transformation from normal to an emergency strategy, spending too much time and lowering reliability. So, training in transformations of strategies would be very important in the training of nuclear and fossil power-plant operators, aircraft pilots, and air traffic controllers.
4. When the time needed by a human operator for transformation of normal strategy into an emergency one is longer than the time for critical changes of the control object, automatic shut-off of the safety system would be activated, because the human operator can not follow control processes. Inability of human operators to transform their strategies synchronously with changes in the control-object dynamic structure, in the absence of active shut-off system, was one of the main causes of Chernobyl Nuclear Power Plant (NPP) catastrophe in 1986 (Venda, 1990).

Rasmussen's methodology of ecological interface design (1986) and Beltracchi's model based information systems with combination of technological and physical structures (1984) are perfect examples of organization of effective transformations of human operator strategies under quick changing conditions from normal to emergency and in the reverse direction at a NPP. Beltracchi proposed using a thermodynamic model of the heat engine Rankine cycle as an external mental model of a nuclear power plant for human operator-computer interface. No new type of model-based display for the human-machine control processes was found necessary; it was shown that with a model based upon the Rankine cycle as an interface, it is much easier for a human to employ a first monitoring strategy to evaluate plant performance. Rasmussen and Vicente (1987) and Beltracchi (1987, 1988) proposed models of analysis with knowledge-based, rule-based, and skill-based behaviors. Transformation methodology allows the study, predicts safety and efficiency changes, and specially organizes transformations between those types of behavior strategies when it is necessary for optimizing the control processes. Yufik, Sheridan, and Venda (1992) provide general theoretical and methodological bases for knowledge measurement in mutual human-machine adaptation. The methodology of transformation dynamics, hybrid intelligence and mutual adaptation in human-machine-environment systems have been successfully used in ergonomic design and in the improvement of many experimental and industrial complex systems in the former USSR (Venda, 1982, 1990).

Transformation Dynamics in Information Systems

The higher level of efficiency of strategy Sc over Sa or Sb, and Sb over Sa, in the emergency experiments (Fig. 4) could be explained with simple information

measures. Higher efficiency means (in this case) lower response time and corresponding task complexity. The natural question is: How does a change in strategy make it possible? Let us analyze the following example. Suppose an observer is taught to identify, i.e., diagnose, 16 states of an object which is described by binary values on a total of 30 dimensions. Each binary value may be thought of as representing either the normal or pathological state for that dimension.

There are two important consequences for practice: a) strategy Sc with more narrow range of factor F values than Sa: (Fc max − Fc min) < (Fa max − Fa min) usually has higher maximal efficiency: Qc max > Qa max. We say in this case that Sc is more specialized and Sa more universal. Obviously, reading by words is more effective in optimal environmental conditions (light, size and style of the fonts) than reading by letters. But the same deviation from optimal conditions will cause greater decreases in efficiency of Sc than of Sa.

In the experiments on reading (Fig. 3) as well as in the emergency experiments (Fig. 4), the strategies used by operators were usually in the sequence Sa-Sb-Sc. Sometimes, after short and unsuccessful trials with strategies Sc and Sb, operators made reverse transformations back to Sb and Sa, and later, to Sb and Sc. That means that decision making processes include using and assessing different cognitive strategies, using various methods of combining (chunking) of information elements as well as direct and reverse transformations of strategies.

Microanalysis of Performance Transformations

In another series of experiments we used a power plant training center where similar emergency situations were modeled. Engineering students (25 in number) participated as observers with 10 trials by each. They were supposed to make decisions, carry out operations, and give commands, like operators at the power plant. The experiments showed the same dynamics of human performance during learning processes as those observed in the previous experiments. The main difference was that in the learning processes, reverse transformations, as well as transformations from Sa directly to Sc, were found in only two students out of the 25. Wavy-like processes were studied in teaching students special skills in speed-reading with use of a metronome, tachistoscope and pacer (fast moving text on the display screen), teaching power-plant operators to perceive information from mnemonic schemes with different information structures and to maintain tracking control with one to six simultaneously perceived dynamic signals (Venda, 1986).

What is especially interesting in transformation dynamics? We found that when analysis of performance becomes more and more detailed, transformation

waves can be seen at any phase of performance and development. For example, transformations occur in long-term individual professional development and the waves are seen during periods of changing of occupation, functions and positions of a person in a company. Besides those waves, macroanalysis will show smooth, monotones processes. More detailed analysis of individual performance during one year, then one month, one day and even during one act of decision making, will reveal more waves in human performance and development. More detailed analysis shows more transformations; less detailed analysis masks many transformation processes and a whole individual career may look like a smooth monotones process. Everybody knows that there are many ups and downs in a career.

Appropriate detailization in the analysis of human performance and development is important for studying transformation processes. Macro and microanalysis are relative definitions. In practice, if transformations are not found with macroanalysis, changing the methodology to more detail (microanalysis) will do so.

Human life is wavy-like. It is inevitable from the point of view of our transformation theory that deep temporary decreases in health, performance efficiency during changes in occupation, life style, sport activity, aging, need to be studied attentively. Adapting to a high level of business or sport activity normally takes much time and includes several big waves. If somebody tries to stop those activities quickly it could be dangerous. Many early deaths of sportsmen have occurred among those who stopped training without necessary reversal waves of transformations back to low load. Every training, sport, or profession leads to deep changes in the organism, shaping step-by-step the appropriate psychological, physiological and biological structures. Transformations of the structures takes time and effort, losses in those periods are inevitable. These are some of the implications of natural law of transformations.

Transformations in Biomechanics and Professional Training

As with any other complex system, the human body allows for a plurality of its structures and respective strategies of behavior. In changing the structures/strategies, their transformations are based on human evolution and on individual development of abilities for mutual adaptation with environment, machines and other people. Such plurality of mental and physical structures/strategies is particularly important when employees are requested to adapt to new technologies, workplaces or to develop work skills.

While the mind and body adapt to the new activity, new strategies and new

muscle groups are incorporated in the task, and error rate and effort are reduced through a natural process of optimization. By recognizing the general law of transformations, training programs can be made more effective and training time reduced. The major benefits of recognizing and using transformation theory are not confined to simple cost efficiencies; the reaction of the physiological system to external stimulus is such that proper adaptation to change can reduce the incidence of stress-related death (such as heart attack) as well as absenteeism in the work place. Since adaptation is essentially the process of adopting new operational strategies, and new strategies are adopted through a behavior compatible both with the old and the new, it is apparent that when the degree of change requested of an individual or of a system is such that very little is in common, drastic failure of the system is imminent.

When a task is re-organized or a new job or level of job is attained, there is an associated stress to which the physiology must adapt. In industry, the purpose of re-organization is to increase productivity and often is predicated on an increase in performance of individuals. Figures 3 and 4 can be used as a qualitative portrayal of the performance benefits of three possible strategies (Sa, Sb, Sc) and the expected performance Q for each. If a task is currently employing strategy Sa, then the individual would shift to strategy Sc to elicit a higher productivity. However, the law of transformations requires that the new strategy will be adopted and adapted through a performance level no greater than that which is common to both strategies. Figure 4 indicates that such a performance efficiency during direct transformation of Sa into Sc is extremely low. The intersection of the strategy curves is at a performance level one-fifth the normal performance using the current strategy. A corporation attempting to introduce new technology without having its personnel comprehend it, may be in exactly the position described above. The possibility of financial disaster is great under those circumstances, particularly if the performance measure is goods produced. However, the focus here is on the complexity level F, associated with performance (Venda, 1990). F could be as any human factor, for example, level of work stimulation. Note that F increases with each new strategy and thus the individual worker must adapt to a new task environment, the biomechanical motion requirements of that environment, and the new biochemical environment that the exogenous and endogenous stimulation produces.

To adopt new work strategies, planning is needed to reach the most lucrative strategy. Refer to Figure 4, where the use of the intermediate strategy Sb, could reach the Sc strategy without the loss in productivity associated with a direct attempt to go from Sa to Sc. In the move from Sa to Sb, the value of performance Q drops to the value of the intercept of those two curves, so performance efficiency is higher than the intercept of curves Sa and Sc, and productivity is

maintained. The productivity saved is the difference in the performances integrated over the time period of the projected strategy changes. The curves of Figure 4 also have a second meaning—a more human meaning. As stimulation level rises, the emotional and psychological stress levels are kept lower if personal productivity can be maintained. Therefore, by approaching the goal through intermediate strategies, stress-related occupational diseases are minimized and the skills of the work-force are retained.

The element of time is important in the adaptation process. The denial of time can result in the stimulation level rising to the point of over-stimulation but forms of biomechanical structure adaptation also require time and a programmed approach (Venda & Thornton-Trump, 1992). While biomechanical adaptations are often not considered in industrial situations, new executives notice that clothes begin to feel tight as they gain weight from days and nights at a desk. The point is, physiology adapts to the level of physical activity such that it becomes dangerous to exert oneself at levels that once were a normal part of a job. It is from this observation and from athletic training programs that information can be drawn on the biomechanical adaptation process and its conformance to the law of transformation.

The energy supply system for human motion is multi-partite. A runner may draw energy from creatine phosphate (CP) as a result of energy release from a phosphate bond as a result of the decomposition reaction. Energy may be gained from glucolysis, as glucose is lysed to lactic acid. A third source of energy is the aerobic oxidation of proteins, fats, and carbohydrates which at the same time replenish the reserves of adenosine triphosphate (ATP). What is important here is the rapidity with which the energy can be accessed and the level at which the activity can be maintained. In training, the runner forces physiological processes to increase the rate of energy release due to decomposition of creatine phosphate as well as the rate at which glycolysis takes place. Each individual has a different potential for the upper limit of this activity and so not all can be good sprinters, but the physiology responds according to the qualitative behavior shown in Figure 6.

Due to the time period of the events a sprinter takes part in, the primary energy reserves used are from creatine phosphate (CP) as shown as curve Q1 of Figure 6, and glycolysis shown as curve Q2. The adaptation of runners to sprinting may be monitored by measuring the energy reserves used from these two sources after they have performed the event for which they are being trained. Since CP has three times the total energy of the glycolysis system, the rate of release of CP is of extreme importance in adapting to sprint events. For long-distance runners, the third energy source, oxidation of fats, proteins and carbohydrates, becomes important. Since the oxidation source has four and a half times

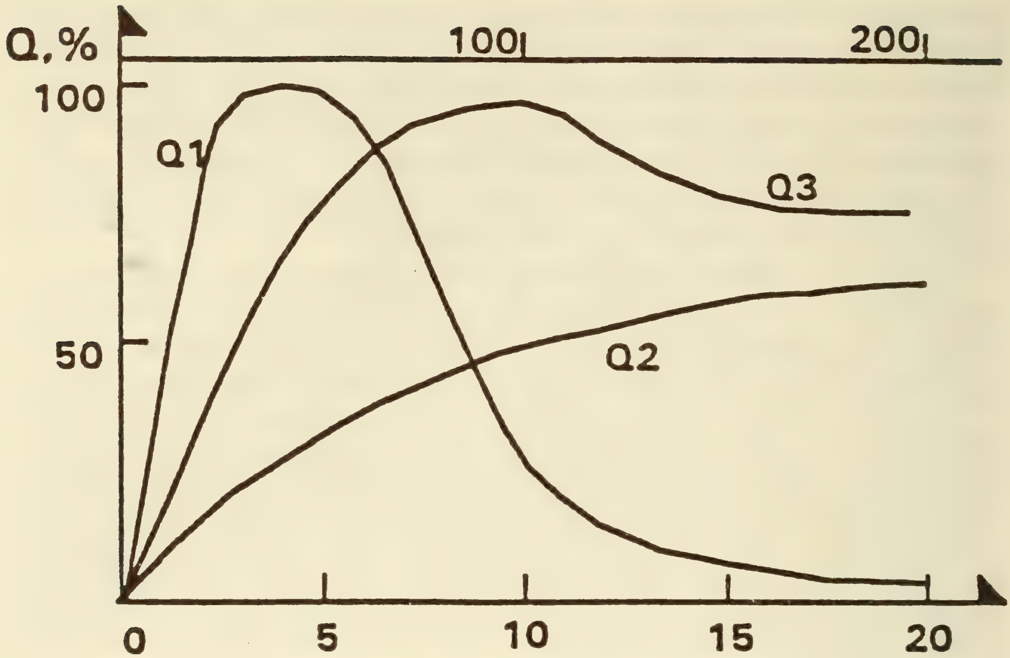

Fig. 6. Locomotor energy sources for a runner. Q1 = creatine phosphate consumption; Q2 = glycolysis; Q3 = oxidation of fats, proteins, and carbohydrates.

less energy than glycolysis, it is the last source of energy to be switched on during locomotor activity. Indeed, sedentary people may never operate at a high rate. In this latter case, physical exhaustion sees an early onset and the stimulation of the organism moves into low performance efficiency level on the characteristic curves (Fig. 3 and 4). In the case of a runner in training, if the exercises undertaken are changed to utilize new muscle groups, the energy release targets are changed, representing a change in strategy for the physiology thus an erosion of performance in sprinting would be seen prior to the hoped-for increase in performance. Such changes have been observed by coaches.

A more common situation in which the law of transformation can be seen to apply is in biomechanical adaptation to a knee injury. In such a case, the phase relationship of the locomotor muscle firings is changed for both the injured and the uninjured limb. The amplitude and duration of the firing of the muscle groups also changes. The reasons for such changes are primarily the attempt of the two nearest uninjured joints to alter activity to compensate for the injured joint, but also may be a pain-avoidance mechanism. The results of the motion restriction and of the phase changes in muscle group activity are to cause the speed of normal locomotion to decrease and to change the floor reaction force

record such that the Fourier components of that record are changed in magnitude and in phase relationship (Thornton-Trump & Sużuki, 1991).

The law of transformation is seen to be valid for many biomechanical and psycho-physiological processes and can be applied in the design of training programs when changes in work-place are such that new sequences of movement, levels of movement, or new groups of tasks, are required of an individual. Parameters can be developed and measured to assess the adaptation level of individuals and to determine training programs appropriate to their ability to adapt.

Productivity can be maintained at a higher level during a transition in strategies when intermediate strategies are used. By designing transitions recognizing the law of transformation, both corporate and individual health can be best served. Of primary significance in the changing of strategies is a recognition of the fact that new strategies can only be adopted through the elements common to both the old and the new strategy. It is through the recognition of this, the law of transformation, that a more reliable basis for the estimation of costs involved in the adoption of new work skills, can be established.

Using Transformation theory leads to many practical observations. For example:

1. The longer time that an individual remains at a stable level (plateau) of strategy Si, the longer will be the time needed for transformation of Si into Si + 1;
2. Individual learning capacity, creativity, adaptability, mutual adaptation with new machines, and environment are dependent on an ability to transform to new strategies, especially distant ones (with big differences between Fi-opt.);
3. It is necessary to teach human operators, pilots, and sportsmen, not only different effective strategies (such as normal and emergency operative conditions) but also how to transform those strategies for appropriate mutual adaptation with the environment. Effective transformations in both directions, forward and reverse, are needed in many types of human performances;
4. In the learning, training and retraining processes, no exams, tests or competitions should be organized during the periods of transformations for structures, strategies, or skills.

Transformations in Manufacturing Technologies

The main ergonomic requirement and methodological principle in the design of productive, reliable and safe technology is mutual, multi-level adaptation between all components of the human-machine-environment system (Venda, 1982). This requirement can be satisfied relatively easily in *constant technology* conditions. But companies with constant technology, management, and social

relations, quickly become noncompetitive. Only companies with the quick ability to change technologies and products are able to survive in difficult times. Industrial ergonomics is a science for mutual multi-level adaptation and Transformation in human-machine-environment systems (HMES).

Ergonomic studies of human-machine-environment interaction in dynamic advanced manufacturing facilities means that the features of machines (workstations, assembly lines, computers, telecommunications, control rooms) and industrial environments (working space, shifts, light, noise, micro climate) are being analyzed and designed in connection with dynamic psychological, physiological, and biomechanical characteristics of human beings.

Study of mutual adaptation and transformation is of particular importance in the implementation of new technologies, advanced manufacturing, management, flexible team work, shifting of work places and worker's functions, professional training and retraining. The law of transformation can be a new basis for multi-level mutual adaptation in dynamic industrial HMES.

There is no general theory or methodology for the analysis and synthesis of the structural dynamics of advanced manufacturing HMES in contemporary human factors and ergonomics. Therefore, analysis and design of such systems will start almost from the beginning, with each design having its own individual character, making such studies very expensive and time consuming and slowing the pace of progress. This is especially visible in the time and effort spent by ergonomists during implementations of computer integrated manufacturing (CIM), Just In Time (JIT), Total Quality Management (TQM), Team Owned Processes, and other innovations in dynamic manufacturing.

The principles of Mutual Adaptation and Transformation are fundamental and generally applicable to all kinds of systems and to every component of the manufacturing system, i.e., human beings, machines, working environment, and to the system as a whole, in its mutual adaptation to other manufacturing, trade, supply, communication, control, and management systems.

Transformation Dynamics and Mutual Adaptation in Ergonomics Development

The general structure and goals of future research are displayed in Fig. 7 which shows the various areas of research and development and how they relate to each other. The main aim of that research program would be to work out the theory, methodology and practical methods of human factors/ergonomics in dynamic manufacturing systems. That aim can be achieved by conducting in parallel a wide range of theoretical, experimental and applied research.

The theory of mutual adaptation in HMES would be oriented toward synthe-

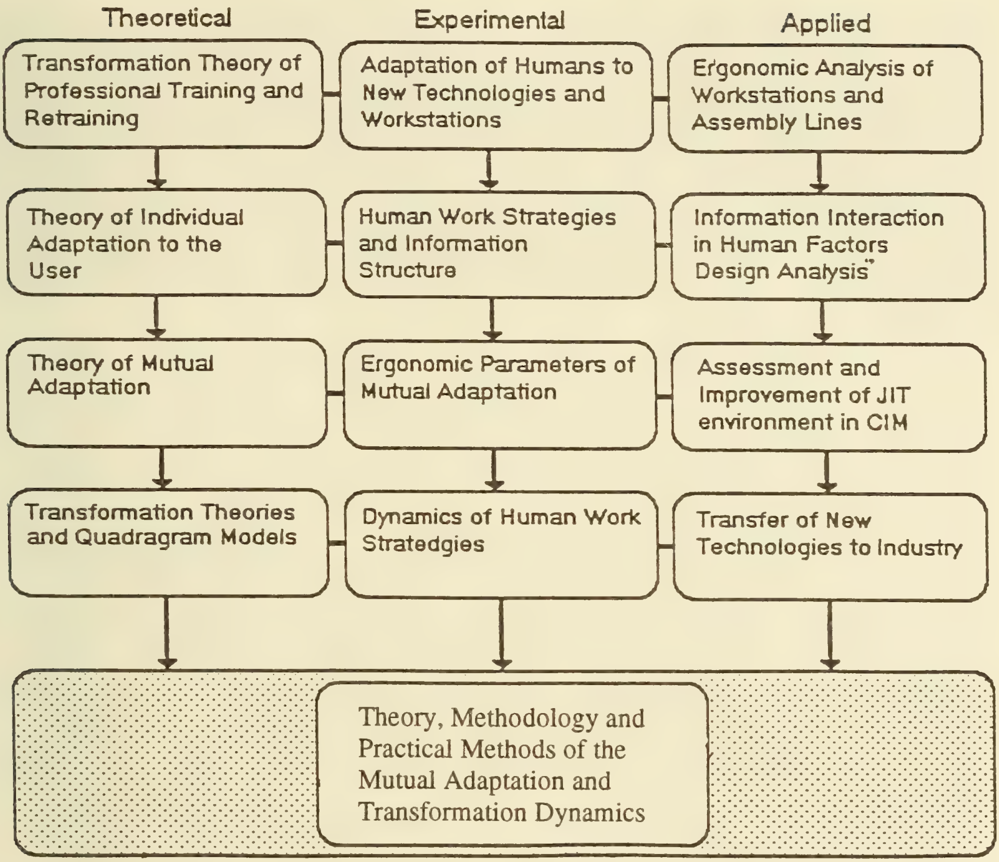

Fig. 7. A structure of research on transformation dynamics and mutual adaptation for Human-Machine-Environment Systems.

sis of two main and traditionally separate directions in psychological and human factors/ergonomics studies: 1. Adaptation of humans to new machines, environment, functions and tasks by using the methods of learning, education, professional and physical training; 2. Adaptation of machines and technological, educational environments to people by using the methods of ergonomic analysis and design. Our proposed methodology of mutual adaptation helps to combine possibilities of both previous tendencies, to make HMES more productive, effective, reliable and safe. In the books by Venda (1982, 1990) and the paper by Yufik, Sheridan, and Venda (1992) the principle of mutual adaptation and transformation theory are used for improving the methodology of analysis of decision making processes, design of information display systems, and decreasing of intellectual complexity of human operator functions. The theory of individual adaptation of machines to the user describes in what way machines need to be designed to fit various types of machine users (Lomov & Venda,

1977; Venda, 1990). The theory of mutual adaptation of humans with machines and the environment describes how the best trade-off for adjusting the human to the machine and environment, and reworking the machine and the environment to the human, can be derived. The theory is being implemented in human factors design, usability testing, interface design and innovative hardware and software solutions, for terminal and user-interface design. The Quadragram Models of the HMES structural transformations (Venda, 1988) describe how a human changes cognitive strategies as learning progresses, and shows how this learning may be sped up.

The experiments on adaptation of humans to new technologies and workstations are based on the transformation theory of learning, training and retraining connected with the analysis of human working skills, strategies of information perception, thinking and decision making, and change of the strategies when a new technology or workstation is implemented. Mutual adaptation of human cognitive strategies and adequate information structures is extremely important for optimal human-computer interaction. The influence of information on human decisions is studied at facilities and with laboratory simulation of human performance in CIM. In addition to the previous stage of experimental studies, an opposite direction of adaptation, the adaptation of a machine to the human individual, will be studied as a second stage. Instead of changing human knowledge, skills, and work strategies, at this stage the local optimum of human-machine system efficiency will be found experimentally by using wide changes of machine characteristics in design, and operative adaptation of information displays, workstations, control rooms, and assembly lines.

In the studies of ergonomic parameters of mutual adaptation which relate to HMES in dynamic manufacturing, criteria and factors of human performance efficiency, complexity, reliability and safety are measured. The third stage of experimental studies on mutual adaptation in human-machine systems should include searching for the global optimum of the systems with coordinated adaptation of human to machine and machine to human. Mutual individual adaptation in human-computer interactive systems is based on recording and computer analysis of observer self reports on psychological factors in decision making. Practical methods of searching for the factors of human operator work complexity and efficiency were described by Venda (1982). These methods allow study of the dynamics of human work strategies when criteria and factors may be changed quantitatively and qualitatively, as in the transformation periods. Fast and effective implementation of new technologies in the manufacturing environment can be organized on the base of mutual adaptation of workers and industrial facilities with dynamic ergonomic criteria, and factors of HMES efficiency. Industrial ergonomic experiments on the transferring of new

technologies have been conducted at the assembly plants of the Northern Telecom Canada, Ltd. Ergonomic analysis, industrial design and improvement of work stations, should facilitate human-centered processes in mutual multi-level adaptation of HMES. Research underway at Northern Telecom concentrates on information display at assembly lines and workstations in CIM and JIT environments. Their objective is to increase the productivity and reliability of individuals, teams, and systems, working under these conditions through the use of the principle of transformation and mutual adaptation. Ergonomic analysis and improvement of the assembly workstation will involve the evaluation of current methods in designing modular quickset workstations that are product specific. The present method of manufacturing is a long flow-line of workstations. Current problems with the straight line process are: decreased communications, fewer opportunities to solve immediate problems and difficulties with smooth KAN-BAN operation (Venda, Strong, Hawaleshka, & Rychlicki, 1992).

Transformation theory is very effective in prediction of dynamics and optimal planning in the process of changing of old technology to the new. For example, if a worker uses professional strategy Sn (Fig. 5) with productivity Qn max, and then technology is changed so the human factor of work complexity F increases from Fn opt to Fa opt very quickly and the worker retains strategy Sn, productivity (quality, efficiency) will decrease to zero (right side of Fig. 5). Hence, transformations of technologies should be synchronized with transformations of the worker's strategies.

Transformation theory is very important also for the problem of job rotation and prevention of repetitive strain injures. An experience at Northern Telecom confirmed that a well defined analysis of job rotation schedules is very important for dynamic manufacturing, where models for dynamic human-machine-environment interaction of the Quadrigram type were worked out (Venda, 1990).

The methods of Transformation dynamics are effective for economic analysis and planning of restructuring of technologies, management and facilities. During a recession and heavy competition, this is of great importance. D. Strong has proposed (Venda, Strong, Hawaleschka, & Rychlicki, 1992) to use transformation dynamics models to compare economic features of different tactics of a manufacturer, who can: 1. Build a new plant somewhere else, in addition to operating the old one, using new workers; and when the new plant functions properly, terminate the workers at the old plant, and sell the old plant and land. 2. Enter a change carefully in one part of his plant, using volunteers to work in this changed area; if the introduction is successful, introduce the change in other areas which require the same type of improvement. 3. Introduce changes on entire facility. Of the three approaches, the third is certainly the most humane

and attractive, but its implementation could be done successfully only on the basis of transformation dynamics and mutual adaptation between all major components of the facility as a HMES. There is another important ergonomic problem, i.e., organizing collective decision-making at every step of transformation to find the best decisions and help everybody to consider the decisions as their own, for the most effective and synchronized implementation of the decisions by every worker, engineer, and manager. This is the problem addressed by the Hybrid Intelligence System (Venda, 1990).

Conclusions

The methodology of transformation dynamics can be effectively used in many spheres of HMES: ergonomic analysis and design, especially in training and re-training; mutual individual adaptation of human-computer dialogue; and synthesis of hybrid intelligence systems for collective decision-making under the most complicated situations. The law of transformation may be used as a very general theoretical basis for study, prediction and improvement of structure changes in humans, machines, and technologies.

Some of the more practical properties of the transformation dynamics processes in advanced dynamic manufacturing human-machine-environment systems could include:

1. The longer the time that a manufacturing facility (firm, human, operator) remains on the plateau of the Si th structure, the longer will be the time for a transformational plateau for the transition from the Si th to the Si + 1 th structure: Si goes to Si + 1.
2. The longer the time that a manufacturing facility (firm, human operator) remains on the plateau of the i-th structure, the shorter will be the time for retransformational plateaus with the back transition from novel strategies Si + 1 back to the Si: Si + 1 goes to Si.
3. Learning capacity and potential for creativity (innovation) of a system, i.e., its mobility, is determined by its ability to execute direct (forward) and reverse (backward) transitions from one distinct strategy to another, and to adopt the most effective strategy in the mutual adaptation of the system with its dynamic environment.
4. Learning efficiency with respect to a range of rapid changes of conditions, at which a system can perform (survive), depends on the batch of mastered strategies and on the rates of their action during the transformational period.
5. An increase in learning time may result in a deterioration of efficiency criteria; the learning process should not be stopped during transformational shifts.
6. Individuals' motivation during learning depends on their personal assessment of prospects and on the degree of mutual adaptation with the environment.
7. Prediction of transformation dynamics is especially difficult. It is much more effective if a collective decision-making system, i.e., hybrid intelligence system, is used.
8. The process of learning or professional training ought to be so planned as to exclude

all kinds of examinations, tests, competitions or responsible assignments, during transformational periods.

9. Cognitive strategies, amenable to transformation are called associated ones, and the method of thinking predicated thereon is associative. A process of thinking, especially a creative one, is based on the transformations of thoughts, images and the like.
10. Quantitative estimates of the fields of events, images and decision making, are the target of studies of various transformations.
11. In many practical cases the initial direct (forward) and the subsequent reverse (back) transformations differ in that the former are clearly of an exploratory, searching character and are performed by the trial-and-error method.
12. Direct and reverse transformation of structures and strategies of the complex system proceed under the same conditions and state of the system.

The law and theory of transformations are general and applicable to any system. This last consequence of the law in application to the former USSR, that contemporary reverse transformation of socialism to capitalism should be in its main aspects as difficult and as similar to the direct transformation which occurred in 1917. These transformation processes have been described in detail (Venda, 1989).

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The 1991 Washington Academy of Sciences Awards Program for Scientific Achievement

C. R. Creveling

National Institute of Diabetes, Digestive, and Kidney Diseases
Bethesda, MD

The Washington Academy of Sciences was founded in 1898 as an affiliation of scientific societies under the sponsorship of the Washington Philosophical Society to conduct, endow, and assist investigation in any department of science. At present the Academy is affiliated with 52 scientific societies. In keeping with the purposes of the Academy, each year, the Committee on Awards for Scientific Achievement accepts nominations and recognizes scientists and science teachers in the Washington metropolitan area who have made outstanding contributions to science that are of merit and distinction. Awards are made for outstanding contributions in the Mathematical and Computer Sciences, the Behavioral and Social Sciences, the Engineering Sciences, the Biological Sciences, and the Physical Sciences. Further, in keeping with the goals of the Academy which include the promotion of excellence in the teaching of science, the Academy also presents awards for the Teaching of Science. These awards include the Leo Schubert Award for excellence in the teaching of science in college and the Bernice Lamberton Award for excellence in teaching science in high school.

Persons selected for recognition are chosen by panels of experts in each of the fields. Nominations are made by Academy members or the public.

In 1991, the Awards were presented at a gala reception held at the Mary Woodward Lasker Center for Health Research and Education, on the grounds of the National Institutes of Health, in Bethesda Maryland, on Thursday, April 18th.

The 1991 awardees were:

Dr. Harold Liebowitz	Distinguished Career in Science
Dr. Robert E. Fay, III	Mathematics and Computer Sciences
Dr. Andrew F. Brimmer	Behavioral and Social Sciences
Dr. David E. Ramaker	Physical Sciences
Dr. Robert J. Lutz	Engineering Sciences
Dr. Miles Herkenham	Biological Sciences
Prof. Glen E. Gordon	Teaching of Science in College

Distinguished Career in Science

The award was granted to DR. HAROLD LIEBOWITZ, Dean Emeritus of the School of Engineering and Applied Science at The George Washington University and the L. Stanley Crane Professor of Engineering. Dr. Liebowitz led the School of Engineering and Applied Science with grace and distinction for over 20 years. Under his leadership the school entered into a period of unprecedented growth in both qualitative and quantitative aspects as reflected in the number of students, faculty, and in research accomplishments. Dr. Liebowitz actively promoted a very successful partnership between the School and the National Aeronautics and Space Administration as exemplified by the Joint Institute for the Advancement of Flight Sciences. In addition Dr. Liebowitz was selected for his scholarly research achievements in fracture mechanics. The Academy recognized Dr. Liebowitz as scholar, engineer, author, educator, and consultant to industry, consultant to the U.S. government and to foreign governments. Dr. Liebowitz was nominated by Prof. Walter K. Kahn, and selected by the Awards Chair, Dr. C. R. Creveling.

Mathematics and Computer Sciences

The award in the Mathematical and Computer Sciences was granted to DR. ROBERT E. FAY, III of the Director's Office of the U.S. Bureau of the Census, for his outstanding contributions to the development of major methodological improvements in survey statistics. Dr. Fay is recognized both nationally and internationally as an insightful innovator in mathematics. His creative applications of sound statistical theory led to important applications in survey sample design, nonsampling error, small area estimation and contingency table analysis. Dr. Fay was nominated by Dr. Edward J. Wegman, President of the Washington Statistical Society, and selected by the Mathematics and Computer Science Committee under the leadership of Dr. Abolghassem Ghaffari.

Behavioral and Social Sciences

The award in the Behavioral and Social Sciences was granted to DR. ANDREW F. BRIMMER, for his contributions in many areas of in general economics, in money, banking, and monetary policy, in international finance and balance of payments and especially for his contributions to the economic development of the black community. For his technical and scientific scholarship in interdependent macroeconomic and social policy. As a result of his contributions, Afroamericans are more successfully integrated into American society, the international financial market is more integrated, and systemic risks in capital markets more fully accounted for. Dr. Brimmer's contributions have led to the construction of a fairer and more efficient American society in a global world. Dr. Brimmer was nominated by Dr. Robert H. Aten and selected by the Committee on Behavioral and Social Sciences under the direction of Dr. Coralee Farlee.

Physical Sciences

DR. DAVID E. RAMAKER received the award in the physical sciences for his many and important theoretical contributions to quantitatively understanding the role of many-body electron phenomena in electron spectroscopies (X-ray, photoelectron, X-ray adsorption) and in stimulated desorption (electron and photon desorption). These contributions has played a major role in the rapid progress of surface science and its technological applications. In particular, he showed that significant new electronic structure information can be obtained from interpretation and understanding of the very complex "many-body" states mapped in the experimental electron spectral line shapes, and that this information could be obtained in a relatively straight-forward and simple manner. Furthermore, he has shown that these very complex "many-body" states are the primary actors in the electron and photon desorption process, and that Auger-electron spectroscopy can be used to map the systems, including gas phase hydrocarbons, condensed molecular gases, solids (silicon, silicon dioxide, diamond, graphite, carbides, and the high temperature superconductors) and atomic and molecular adsorbates on surface (chemisorbed ethylene and carbidic carbon). Dr. Ramaker was nominated by Dr. James S. Murday of the Naval Research Laboratory, and selected by the Committee on the Physical Sciences chaired by Dr. Richard K. Cook.

Engineering Sciences

The award in the Engineering Sciences was granted to DR. ROBERT J. LUTZ, of the National Institutes of Health, for his creative application of engi-

neering science and practice in biomedical research and his scholarly contributions to the study of fluid mechanics. Dr. Lutz made significant contributions to the development of practical vascular models in persons and in the development of physiological and pharmacokinetic models of drug and toxin distribution. Dr. Lutz was nominated by Dr. Robert L. Dedrick, and selected by the Committee on Engineering Sciences under the direction of Marianne P. Vaishnav.

Biological Sciences

The award in the Biological Sciences was granted to DR. MILES HERKENHAM, Chief of the Section on Functional Neuroanatomy, National Institute of Mental Health, for his pioneering development of high resolution, autoradiographic techniques for the localization of receptors in the central nervous system. Dr. Herkenham has made major contributions toward understanding the nature of affective disorders in man and toward an understanding of the mechanisms of action in the brain of therapeutic agents and drugs of abuse. Dr. Herkenham was nominated by Dr. Kenner C. Rice of the Laboratory of Medicinal Chemistry, National Institute of Diabetes and Digestive and Kidney Diseases, and was selected by the Committee on Biological Sciences under the direction of Dr. C. R. Creveling.

Leo Schubert Award for Teaching of Science in College

The Leo Schubert award for Teaching of Science in College was granted to PROFESSOR GLEN E. GORDON of the University of Maryland, for his development and dynamic teaching of environmental chemistry. Professor Gordon has provided both science and non-science students with a knowledgable basis for making decisions on questions ranging from nuclear weapons to fuel economy in cars. He has provided science students a basis for making critical evaluations of environmental and economic factors in our society and the world and an appreciation of the risks to which people may be subjected. Professor Gordon was nominated by Dr. Alice C. Mignerey, and selected by the Leo Schubert Award Committee under the direction of Marylin F. Krupsaw.

Bernice Lamberton Award for Teaching of Science in High School

No nominations were received for this award.

After a reception for the awardees, a lecture was delivered by the winner of the Award in the Biological Sciences, Dr. Miles Herkenham, entitled *Understanding drug and neurotransmitter actions in the brain.*

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The Bylaws of the Washington Academy of Sciences[1]

ARTICLE I. OBJECTIVES

Section 1. The objectives of the Washington Academy of Sciences (hereinafter called the Academy) shall be: (a) to stimulate interest in the sciences, both pure and applied; and (b) to promote their advancement and the development of their philosophical aspects by the Academy membership and through cooperative action by the Affiliated Societies.

Section 2. These objectives may be attained by, but are not limited to: (a) publishing a periodical, occasional scientific monographs and such other books or pamphlets as may be deemed desirable; (b) conducting public lectures of broad scope and interest in the fields of science; (c) sponsoring a Washington Junior Academy of Sciences (WJAS); (d) promoting science education and a professional interest in science among people of high school and college age; (e) accepting or making grants of funds to aid special research projects; (f) convening symposia, both formal and informal, on any aspects of science; (g) calling scientific conferences; (h) organizing or assisting in scientific assemblies or bodies; (i) cooperating with other academies and scientific organizations; (j) awarding prizes and citations for special merit in science; (k) maintaining an office and staff to aid in carrying out the objectives of the Academy.

ARTICLE II. MEMBERSHIP

Section 1. The Academy shall be comprised of individuals and Affiliated Societies. Throughout this document when reference is made to individuals, the use of "he" shall be interpreted as "he or she."

[1] The revised Bylaws of the Washington Academy of Sciences dated May 1982 were replaced by a March 1984 edition. The 1984 version was found to have many imperfections. The effort to correct resulted in a April 1, 1988 version, followed quickly by a April 29, 1988 version which took away the vote of representatives of Affiliated Societies. The subsequent May 1989 version returned the vote of the affiliates but other problems came to the forefront. A proposed version dated May 24, 1990 was mailed to the membership for consideration with a cut-off date of August 9, 1990. The revisions were approved by majority vote of the Membership.

Section 2. Members shall be individuals who are interested in and will support the objectives of the Academy and who are otherwise acceptable to at least two-thirds of the Committee on Membership. A letter or application form requesting membership and signed by the applicant may suffice for action by Committee; approval by the Committee constitutes election to membership.

Section 3. Fellows shall be individuals who by reason of original research or other outstanding service to the sciences, mathematics, or engineering are deemed worthy of the honor of election to Academy fellowship.

Section 3(a). Nominations of fellows shall be presented to the Committee on Membership on a form approved by the Committee. The form shall be signed by the sponsor (a Fellow who has knowledge of the nominee's field), and shall be endorsed by at least one other Fellow. An explanatory letter from the sponsor and supporting material shall accompany the completed nomination form.

Section 3(b). Election to fellowship shall be by vote of the Board of Managers upon recommendation of the Committee on Membership. Final action on nominations shall be deferred at least one week after presentation to the Board of Managers, where two-thirds of the vote cast shall be necessary to elect. The election process shall be completed upon submission of the processed nomination forms to the Vice President for Membership Affairs.

Section 3(c). Each individual (not already a Fellow) who has been chosen to be the recipient of an Academy Award for Scientific Achievement shall be considered nominated for immediate election of fellowship. The election process shall be completed upon submission of the standard nomination forms to the Vice President for Membership Affairs, thus obviating the procedures of Sections 3(a) and 3(b) of this Article.

Section 3(d). Any fellow of the Academy may recommend in writing that an individual of national eminence be considered for immediate election to fellowship by the Board of Managers, without the necessity of compliance with the procedures of Sections 3(a) and 3(b) of this Article. Following approval by the Board of Managers, the election process shall be completed upon submission of the standard nomination forms to the Vice President for Membership Affairs.

Section 4. Patrons. Members or fellows who have given to the Academy not less than one thousand dollars, or its equivalent in property or tangible assets, shall be eligible for election by the Board of Managers as Patrons of the Academy (for life). Following approval by the Board of Managers, the election process shall be completed when suitable documentation has been submitted to the Vice President for Membership Affairs.

Section 5. Life Members or *Life Fellows* shall be those individuals who have made a single payment in accordance with Article II, Section 11(a) in lieu of annual dues.

Section 6. Members or fellows in good standing who are retired and are no longer engaged in regular gainful employment may be placed in emeritus status. Individuals in emeritus status shall be designated *Emeritus Member* or *Emeritus Fellow* as appropriate. Upon request to the Vice President for Membership Affairs for transfer to this status, they shall be relieved of further payment of dues, beginning with the following January first; shall retain rights to hold office and attend meetings; shall receive notices of meetings without charge; and at their request, shall be entitled to receive the Academy periodical at cost. This transfer shall be completed when the Treasurer and the Vice President for Administrative Affairs have been so notified.

Section 7. Members or fellows living more than 50 miles from the White House, Washington, DC shall be classed as *Nonresident Members* or *Nonresident Fellows.*

Section 8. An election to any dues-paying class of membership shall be void if the candidate does not within three months thereafter pay his dues or satisfactorily explain his failure to do so.

Section 9. Former members or fellows who resigned in good standing may be reinstated upon application to the Vice President for Membership Affairs for approval by the Board of Managers. No reconsideration of the applicant's qualifications need be made by the Membership Committee in these cases.

Section 10. Affiliated Societies. Bona fide scientific societies may apply for affiliation with the Academy by furnishing to the Secretary of the Academy an outline of their objectives, organizational structure and requirements for membership in their society. The Secretary will transmit the application to the Policy and Planning Committee for review and recommendation for action by the Board of Managers.

Section 10(a). Each Affiliated Society shall select one of its members who is also a member or fellow of the Academy to serve as its representative to the Board of Managers. The representative shall serve until replaced by his society.

Section 10(b). Each Affiliated Society shall cooperate with the Academy in sponsoring joint meetings of general scientific interest.

Section 11. Dues. Annual dues for each member class shall be fixed by the Board of Managers. No dues shall be paid by Emeritus members, Emeritus fellows, Life members, Life fellows, Patrons, or Affiliated Societies.

Section 11(a). Members and fellows in good standing may be relieved of further payment of dues by making a single payment that has a value equal to ten years of dues current at the time of payment. (see Article II, Section 5) Such persons are to be identified as Life Members or Life Fellows as appropriate. Income from this source shall be identified as the Life Membership Endowment Fund (LMEF) and shall be monitored in perpetuity by three *Trustees* who are resident Life Members or resident Life Fellows. The Trustees shall direct the investment of the Fund (LMEF) in a conservative action and turn over to the Treasurer all interest from such investments. Trustees shall serve for the duration of life or until the change to nonresident status or the onset of permanent disability or resignation.

Section 11(b). Individuals whose dues are in arrears for one year (counting from the "dues payable date" on the latest dues payment bill) shall neither be entitled to receive Academy publications nor to vote in Academy elections.

Section 11(c). Individuals whose dues are in arrears for twenty-four (24) months (counting from the "dues payable date" on the latest dues payment bill) shall be dropped from the rolls of the Academy, upon notice to the Board of Managers, unless otherwise directed. Those who have been dropped from membership for nonpayment of dues may be reinstated upon approval of the Board of Managers and upon payment of back dues for two years together with dues for the year of reinstatement.

ARTICLE III. ELECTED OFFICERS and BOARD MEMBERS

Section 1. Officers of the Washington Academy of Sciences shall be President, President-Elect, Vice President for Administrative Affairs, Vice President for Membership Affairs, Vice President for Affiliate Affairs, Vice President for WJAS Affairs, Secretary, and Treasurer. All shall be chosen from resident fellows of the Academy.

Section 2. The President shall appoint all committees and such nonelective officers as are needed unless otherwise directed by the Board of Managers or provided in the bylaws. He (or his substitute: the President-Elect, the Vice President for Administrative Affairs, the Vice President for Membership Affairs, the Vice President for Affiliate Affairs, the Vice President for WJAS Affairs, the

Secretary, or the Treasurer, in that order) shall preside at all meetings of the Academy, the Board of Managers and the Executive Committee.

Section 3. The President-Elect shall succeed to the office of President following one term as President-Elect. The President-Elect shall serve as Chair of the *Program Planning Committee* to arrange speakers and meeting places for the following year (the year in which the President-Elect succeeds to President). Other duties may be assigned by the Board of Managers.

Section 4. The Vice President for Membership Affairs shall have general responsibilities for committees related to membership: the Membership Committee, the Membership Promotion Committee, and the Committee on Awards for Scientific Achievement. Other duties may be assigned by the Board of Managers.

Section 5. The Vice President for Administrative Affairs shall have general responsibility for operation of the Business Office of the Academy and the Journal of the Washington Academy of Sciences, and such other duties as assigned by the Board of Managers. He shall oversee the activities of the Editorial Advisory Committee, the Ways and Means Committee, and the Office Manager.

Section 6. The Vice President for Affiliate Affairs shall serve as Chair of the Affiliated Society Representatives. He shall carry out such other duties as assigned by the Board of Managers.

Section 7. The Vice President for WJAS Affairs shall have general responsibility for the committees relating to organizing and maintaining the Junior Academy (WJAS). He shall interface with the Joint Board on Science and Engineering Education, and shall carry out such other duties as assigned by the Board of Managers.

Section 8. The Secretary shall record and distribute the minutes of the meetings of the Board of Managers and such other meetings as the Board of Managers may direct. He shall conduct all correspondence relating thereto, except as otherwise provided, and shall be the custodian of the Corporate Seal of the Academy.

Section 9. In cooperation with the Vice Presidents for the functional areas described in Sections 4, 5, 6, and 7, above, the *Treasurer* shall be responsible for preparing the Budget of the Academy and submitting it to the Board of Managers for approval. The Treasurer shall also be responsible for distributing to the Board of Managers in a timely manner records of funds received and expended. The Treasurer shall be responsible for maintaining records of funds deposited in banks or other savings instruments. The Treasurer and/or other designated

persons shall sign checks for disbursements of funds as directed by the Board of Managers. The Treasurer shall prepare annual reports as required by the Internal Revenue Service, the U.S. Postal Service, etc. He shall deposit and disburse funds of the Washington Junior Academy of Sciences.

Section 10. The President and the Treasurer, as directed by the Board of Managers, shall jointly assign securities belonging to the Academy and endorse financial and legal papers necessary for the uses of the Academy, except those relating to current expenditures authorized by the Board of Managers and those under cognizance of the Life Membership Endowment Fund Trustees. In case of disability or absence of the President or Treasurer, the Board of Managers may designate the President-Elect or another elected officer as Acting President and/or another elected officer of the Academy as Acting Treasurer, who shall perform the duties of these offices during such disability or absence.

Section 11. Two members or fellows of the Academy shall be elected each year to serve a three-year term as *Members of the Board of Managers.* To initiate staggered terms or to fill vacancies, additional Members of the Board of Managers may be selected in the annual election.

Section 12. The newly elected officers and Members of the Board of Managers shall take office at the close of the annual meeting, when the President-Elect of the previous year becomes President.

ARTICLE IV. APPOINTED OFFICERS

Section 1. An *Office Manager* shall be appointed by the Board of Managers. The Office Manager shall be responsible for the routine business operation of the Academy. The Board of Managers shall determine the type of business activity (volunteer workers or contract workers) and the amount of funds to be allocated to the business office.

Section 2. An *Editor* for the Journal of the Washington Academy of Sciences shall be appointed by the Board of Managers. The Editor shall be responsible to the Vice President for Administrative Affairs for administrative policy and related activities.

Section 3. An *Archivist* may be appointed by the President. If appointed he shall maintain the permanent records of the Academy, including important records which are no longer in current use by the Secretary, Treasurer or other officer, and such other documents and material as the Board of Managers may direct.

ARTICLE V. BOARD OF MANAGERS

Section 1. The activities of the Academy shall be guided by the Board of Managers, consisting of the President, the President-Elect, the immediate Past President, the four Vice Presidents, the Secretary, Treasurer, the six Members of the Board of Managers, and one representative from each of the Affiliated Societies. The elected officers of the Academy shall hold like offices on the Board of Managers.

Section 2. The Board of Managers shall set the dues for individual members and the minimum contribution for Patrons. For prolonged, diligent and well-documented service in the administrative work of the Academy the Board of Managers may recognize such service of a member or fellow by citation including dues paid for Life.

Section 3. The Board of Managers shall transact all business of the Academy not otherwise provided for. A quorum of the Board shall be one third of the membership of the Board of Managers. To be eligible to vote the officer or member of the Board of Managers must be in good standing, casting one vote only regardless of the number of offices or Affiliated Societies that he may represent.

Section 4. The Board of Managers may provide for such standing and special committees as it deems necessary.

Section 5. The Board of Managers shall have power to fill all vacancies in its elected membership until the next election. This does not apply to the offices of the President and Treasurer or to representatives of Affiliated Societies.

ARTICLE VI. COMMITTEES

Section 1. An *Executive Committee* shall have cognizance of Academy finances by reviewing the Treasurer's monthly reports of budgeted expenses and anticipated income, and by reviewing the status of several internal accounts: the Life Membership Endowment Fund, the I.R.S. Form 990 accounts, the Postal Accounts, the WJAS Account, etc.

Section 2. The Executive Committee shall meet one-half hour prior to the scheduled meeting of the Board of Managers to anticipate and obviate budgetary imbalances. The results of such actions shall be reported to the Board of Managers following the Treasurer's report.

Section 3. The Executive Committee shall consist of the incumbent elected officers of the Board of Managers plus two non-elected members of the Board of Managers chosen by the Board of Managers.

Section 4. Committees under the cognizance of the President are the Executive Committee, the Nominating Committee, the Policy and Planning Committee, the Audit Committee, and such other committees as shall be determined by the Board of Managers.

Section 5. Committees under the cognizance of the President-Elect are the Program Planning Committee and such other committees as shall be determined by the Board of Managers.

Section 6. Committees under the cognizance of the Vice President for Membership Affairs are the Membership Committee, the Membership Promotion Committee, the Committee on Awards for Scientific Achievement, and such other committees as shall be determined by the Board of Managers.

Section 7. Committees under the cognizance of the Vice President for Administrative Affairs are the Editorial Advisory Committee, the Ways and Means Committee, and such other committees as shall be determined by the Board of Managers.

Section 8. Committees under the cognizance of the Vice President for WJAS Affairs are the Committee on the Encouragement of Science Talent, Committee on Grants-in-Aid for Scientific Research, and such other committees as shall be determined by the Board of Managers.

Section 9. The President shall appoint from the Academy membership such committees as are authorized by the Board of Managers and such special committees as necessary to carry out its functions. Committee appointments shall be staggered as to term whenever it is determined by the Board of Managers to be in the interest of continuity of committee affairs.

Section 10. The President, with the approval of the Board of Managers, shall appoint a Nominating Committee of six fellows of the Academy, (see Article VI, Section 4) at least one of whom shall be a Past-President of the Academy, and at least three of whom shall have served as representatives of Affiliated Societies for at least one year.

Section 11. The Nominating Committee shall prepare a slate listing one or more persons for each of the offices of President-Elect, the four Vice Presidents, Secretary, Treasurer, and four or more persons for the two Members of the Board of Managers whose terms expire after three years and at least two persons

for each vacant unexpired term of such position (see Article III, Section 11). The slate shall be presented for approval at the meeting in December. Not later than December 15, the Vice President for Administrative Affairs shall forward to each Academy member and fellow an announcement of the election, the Committee's nomination for the offices to be filled, and a list of incumbents. Additional candidates for such offices may be proposed by any member or fellow in good standing by letter received by the Vice President for Administrative Affairs not later than January 3. The letter shall include the concurrence of the nominees and the names of 25 members or fellows making the proposal. Upon verification by the nominating committee the names shall be entered on the ballot. The Board shall remind members and fellows of the foregoing option with the distribution of the preliminary slate.

Section 12. Not later than February 15, the Vice President for Administrative Affairs shall prepare and mail ballots to members and fellows. Independent nominations shall be included on the ballot, and the names of the nominees shall be arranged in alphabetical order. When more than two candidates are nominated for the same office, the voting shall be by preferential ballot in a manner prescribed by the Board of Managers. The ballot shall contain a notice to the effect that votes not received by the Vice President for Administrative Affairs before the first Thursday of March, and votes of individuals whose dues are in arrears for one year or more, will not be counted. The Committee of Tellers shall count the votes and report the results at the April Meeting of the Board of Managers.

ARTICLE VII. MEETINGS OF THE ACADEMY

Section 1. The annual meeting of the Academy shall be held each year in May. It shall be held on the third Thursday of the month unless otherwise directed by the Board of Managers. At this meeting, the reports of the President-Elect and the several Vice Presidents, the Secretary, the Treasurer, and the Committee of Tellers shall be presented.

Section 2. Meetings of the Board of Managers shall be held as called by the President, or in his absence by the Secretary, or within ten days after a written request by six members of the Board of Managers has been sent to all members of the Board of Managers. Regular meetings of the Board of Managers shall be set preferably for a fixed place, hour, day of week, and sequence of months excepting July and August.

Section 3. Other meetings may be held at such time and place as the Board of Managers may determine.

Section 4. The rules contained in "Robert's Rules of Order Revised" shall govern the Academy in all cases to which they are applicable, and in which they are not inconsistent with the bylaws or special rules of order of the Academy.

ARTICLE VIII. REMOVAL FROM OFFICE

Section 1. Members of the Board of Managers and the Executive Committee shall assure that all business of the Academy is conducted in the highest spirit of ethics and integrity. This includes the absence of a conflict of interest, which is defined as the acceptance of positions or contracts with the Academy which would result or give the appearance of resulting in a profit or other material advantage to an officer of the Academy. NOTE: Article V, Section 2 is considered a service citation by the Academy and as such is an exception.

Section 2. If any member of the Board of Managers or the Executive Committee is found by a vote of two-thirds of the Board of Managers to have violated the spirit of ethics and integrity or the conflict of interest requirements, he or she shall be removed from office.

Section 3. The position vacated by such removal shall be filled temporarily by appointment by the Board of Managers until the next scheduled election or regular appointment to the affected position.

Section 4. When for approved Academy obligations, circumstances necessitate payment by persons other than the Academy officers who sign checks, reimbursement to such persons shall be made only when appropriate documentation is submitted to the Treasurer of the Academy.

ARTICLE IX. COOPERATION

Section 1. The term "Affiliated Societies" in their order of seniority (see Article II, Section 10) shall be held to cover the:
Philosophical Society of Washington;
Anthropological Society of Washington;
Biological Society of Washington;
Chemical Society of Washington;
Entomological Society of Washington;
National Geographic Society;

Geological Society of Washington;
Medical Society of the District of Columbia;
Columbia Historical Society;
Botanical Society of Washington;
Society of American Foresters, Washington Section;
Washington Society of Engineers;
Institute of Electrical and Electronics Engineers, Washington Section;
American Society of Mechanical Engineers, Washington Section;
Helminthological Society of Washington;
American Society for Microbiology, Washington Branch;
Society of American Military Engineers, Washington Post;
American Society of Civil Engineers, National Capital Section;
Society for Experimental Biology and Medicine, District of Columbia Section;
American Society for Metals, Washington Chapter;
American Association for Dental Research, Washington Section;
American Institute of Aeronautics and Astronautics, National Capital Section;
American Meteorological Society, District of Columbia Chapter;
Insecticide Society of Washington, now Pest Science Society of Washington;
Acoustical Society of America, Washington Chapter;
American Nuclear Society, Washington Section;
Institute of Food Technologists, Washington Section;
American Ceramic Society, Baltimore-Washington Section;
Electrochemical Society, National Capital Section;
Washington History of Science Club;
American Association of Physics Teachers, Chesapeake Section;
Optical Society of America, National Capital Section;
American Society of Plant Physiologists, Washington Area Section;
Washington Operations Research Council, now Washington Operations Research and Management Science Council;
Instrument Society of America, Washington Section;
American Institute of Mining, Metallurgical, and Petroleum Engineers, Washington Section;
National Capital Astronomers;
Maryland-District of Columbia-Virginia Section of the Mathematical Association of America;
District of Columbia Institute of Chemists;
District of Columbia Psychological Association;
Washington Paint Technical Group;
American Phytopathological Society, Potomac Division;
Society for General Systems Research, Metropolitan Washington Chapter;

Human Factors Society, Potomac Chapter;
American Fisheries Society, Potomac Chapter;
Association for Science, Technology and Innovation;
Eastern Sociological Society;
Institute of Electrical and Electronics Engineers, Northern Virginia Chapter;
Association for Computing Machinery, Washington Chapter;
Washington Statistical Society;
Institute of Industrial Engineers;
Society of Manufacturing Engineers;
and such others as may be hereafter recommended by the Board of Managers and elected by two-thirds of the members of the Academy voting, the vote being taken by correspondence. A society may be released from affiliation on recommendation of the Board of Managers, and the concurrence of two-thirds of the members of the Academy voting.

Section 2. The Academy may assist the affiliated scientific societies of Washington in any matter of common interest, as in joint meetings, or in the publication of a joint directory; provided it shall not have power to incur for or in the name of one or more of these societies any expense or liability not previously authorized by said society and societies, nor shall it without action of the Board of Managers be responsible for any expenses incurred by one or more of the Affiliated Societies.

Section 3. No Affiliated Society shall be committed by the Academy to any action in conflict with the charter, constitution, or bylaws, of said society, or its parent society.

Section 4. The Academy may establish and assist a Washington Junior Academy of Sciences for the encouragement of interest in science among students in the Washington area of high school and college age.

ARTICLE X. AWARDS AND GRANTS-IN-AID

Section 1. The Academy may award medals and prizes or otherwise express its recognition and commendation of scientific work of high merit and distinction in the Washington area. Such recognition shall be given only on approval by the Board of Managers of a recommendation by the Committee on Awards for Scientific Achievement.

Section 2. The Academy may receive or make grants to aid scientific research in the Washington area. Grants shall be received or made only on approval by the

Board of Managers of a recommendation by the Committee on Grants-in-Aid for Scientific Research.

ARTICLE XI. AMENDMENTS

Section 1. Amendments to these bylaws shall be proposed by the Board of Managers and submitted to the members of the Academy in the form of a mail ballot accompanied by a statement of the reasons for the proposed amendment. A two-thirds majority of those members voting is required for adoption. At least two weeks shall be allowed for the ballots to be returned.

Section 2. Any Affiliated Society or any group of ten or more members may propose an amendment to the Board of Managers in writing. The action of the Board of Managers in accepting or rejecting this proposal to amend the bylaws shall be by a vote on roll call, and the complete roll call shall be entered in the minutes of the meeting.

ARTICLE XII. DISTRIBUTION OF FUNDS ON DISSOLUTION

In the event of a liquidation, dissolution, termination or winding up of the Washington Academy of Sciences (whether voluntary, involuntary, or by operation of law) the total assets of the Washington Academy of Sciences shall be distributed by the Board of Managers, provided that none of the property or assets of the Washington Academy of Sciences shall be made available in any way to any individual, corporation or other organization, except to one or more corporations, or other organizations which qualify as exempt from federal income tax under Section 501(c)(3) of the U.S. Internal Revenue Code of 1954, as may be from time to time amended.

ARTICLE XIII. PURPOSE

The Washington Academy of Sciences is organized exclusively for charitable, educational, and scientific purposes, including, for such purposes, the making of distributions to organizations that qualify as exempt organizations under Section 501(c)(3) of the U.S. Internal Revenue Code (or the corresponding provision of any future United States Internal Revenue Law.).

ARTICLE XIV. CONTROL OF FUNDS, ACTIVITIES

No part of the net earnings of the Washington Academy of Sciences shall inure to the benefit of, or be distributable to its members, trustees, officers, or other private persons, except that the Washington Academy of Sciences shall be authorized and empowered to pay reasonable compensation for services rendered, and to make payments and distributions in furtherance of the purposes set forth in Article XII hereof. No substantial part of the activities of the Washington Academy of Sciences shall be the carrying on of propaganda, or otherwise attempting to influence legislation, and the Washington Academy of Sciences shall not participate in, or intervene in (including the publishing or distribution of statements) any political campaign on behalf of any candidate for public office. Notwithstanding any other provision of these Articles, the Washington Academy of Sciences shall not carry on any other activities not permitted to be carried on (a) by an association exempt from Federal income tax under Section 501(c)(3) of the Internal Revenue Code of 1954 (or the corresponding provision of any future United States Internal Revenue Law) or (b) by an association, contributions to which are deductible under Section 170(c)(2) of the U.S. Internal Revenue Code of 1954 (or the corresponding provision of any future United States Internal Revenue Law).

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1991 Washington Academy of Sciences Membership Directory

M = Member; F = Fellow; LF = Life Fellow; LM = Life Member; EM = Emeritus Member; EF = Emeritus Fellow; NRF = Non-Resident Fellow.

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